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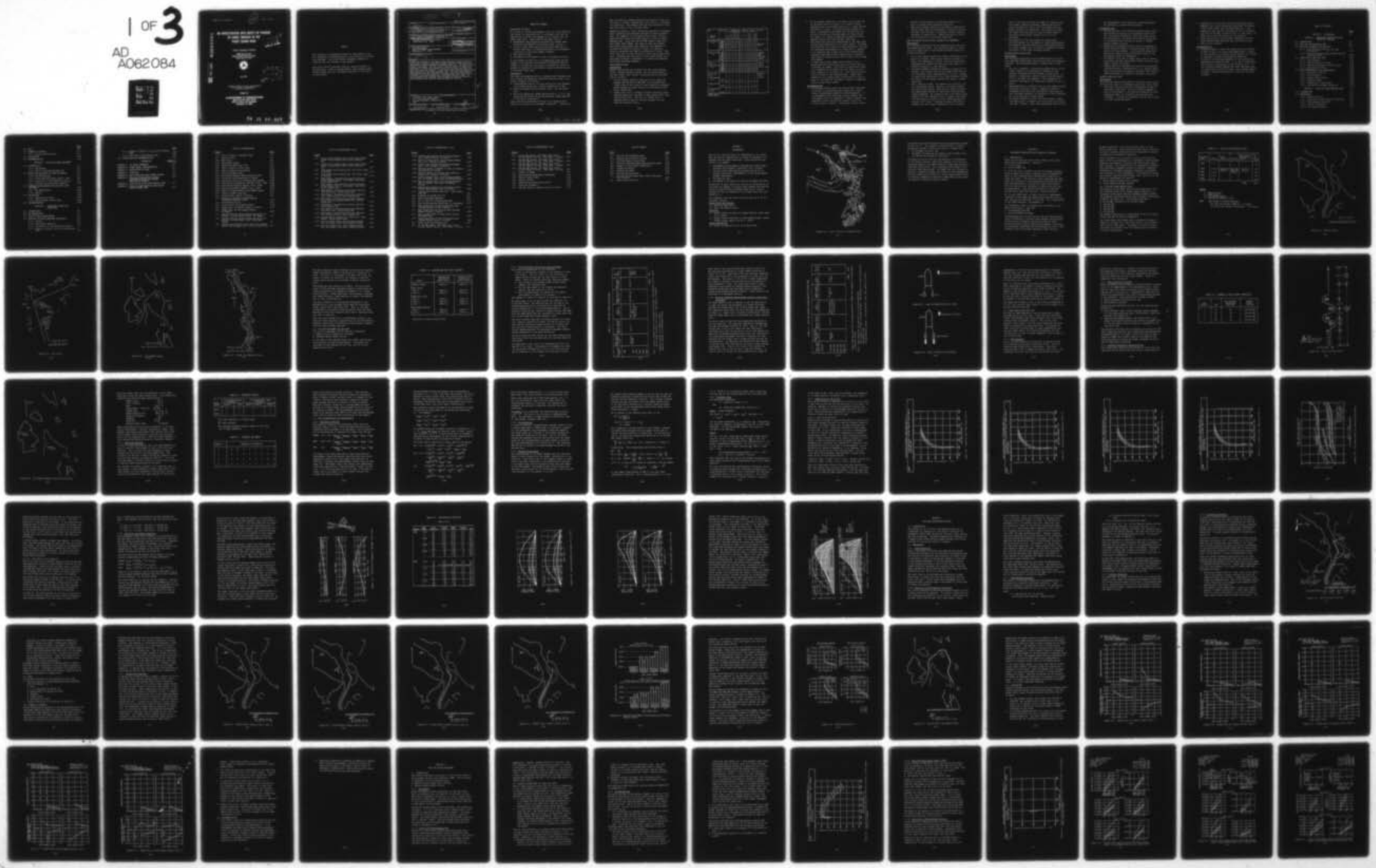

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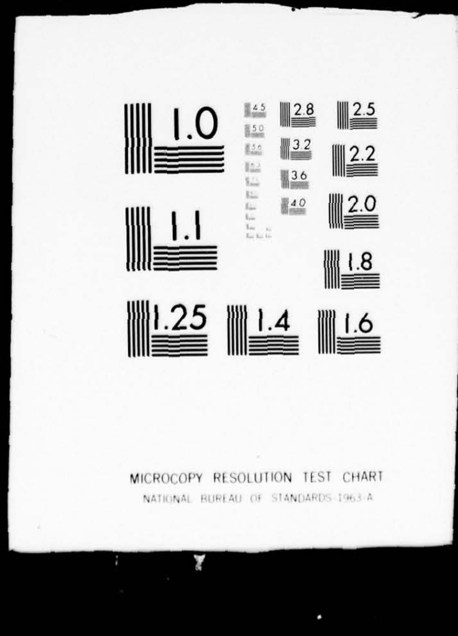

Report No. CG-D-79-78

Vol. 1 of 2

AN INVESTIGATION INTO SAFETY OF PASSAGE OF LARGE TANKERS IN THE PUGET SOUND AREA

J. Riek, S. Tenenbaum, W. McIlroy

CAORF Research Staff
National Maritime Research Center
Kings Point, NY 11024

July 1978

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S.DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20590

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18 USCG 19 D-79-78-VOL-1

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-79-78		

4. Title and Subtitle
6 An Investigation into Safety of Passage of Large Tankers in the Puget Sound Area. Volume 1.
A062085

5. Report Date
11 Octob[redacted]978

6. Performing Organization Code

7. Author(s)
10 J. Riek, S. Tenenbaum W. McIlroy

8. Performing Organization Report No.

9. Performing Organization Name and Address
National Maritime Research Center
Kings Point, N.Y. 11024

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
15 MIPR-Z 70099-8-843822

12. Sponsoring Agency Name and Address
U.S. Coast Guard
Office of Research and Development
Washington, D.C. 20590

13. Type of Report and Period Covered
9 FINAL rept.

14. Sponsoring Agency Code

15. Supplementary Notes
12 203p.

16. Abstract
A study was conducted at the Computer Aided Operations Research Facility to investigate the safety of passage of tankers through the Puget Sound area under maximum credible adverse environmental conditions. The study was conducted in two phases: off-line, using a computer program to simulate the performance of various size tankers, and on-line utilizing the CAORF simulator with human test subjects. In each phase, there were two types of runs: track keeping runs, and failed equipment runs. The track keeping results indicated that all ships were able to navigate safely under the extreme environmental conditions provided they maintained sufficient speed. The failed equipment runs indicated that tug support of ships was required to avoid grounding after suffering steering/propulsion failures.

A062 085

17. Key Words	18. Distribution Statement
oil tanker, Puget Sound. simulation, off-line, track keeping, tug boat assistance., man-in-the-loop.	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

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EXECUTIVE SUMMARY

OBJECTIVES OF STUDY

As a result of recent developments, the U.S. Coast Guard has been given the responsibility to investigate the need for regulations to govern the passage of oil tankers into the Puget Sound area. These regulations might involve:

- Recommended safe maximum or minimum ship speeds under specified environmental conditions (wind, current).
- Critical areas where special precautions might be required (tug escort or constraints based on environmental conditions or ship displacement tonnage).
- The need for tugs.
- Procedures to be adopted in case of equipment failures.

At the request of the U.S.C.G. a simulation study was performed at the Computer Aided Operations Research Facility (CAORF) to acquire data with which to assess the safety of passage of different sized tankers through selected straits in the Puget Sound area.

METHODOLOGY

The study investigated safety of passage under maximum credible adverse environmental conditions (40-knot winds, up to 6-knot currents) as follows:

- Track-keeping runs in critical portions of four passages in the Puget Sound area, without assistance of tugs.
- Runs with engine failure during a turn. No tug assistance.
- Runs with engine and rudder failure with 0, 2, or 4 tugs assisting the vessel by providing astern thrust parallel to the ship's centerline.

These runs were performed "off-line" on a computer with maneuvers dictated by a programmed "autopilot". These runs

were followed by a manned simulation of several of the off-line runs to examine comparatively the results of the computer simulation. The tankers used and the conditions of the runs are listed in the following table.

Computer printouts of ship tracks were analyzed to determine which conditions and maneuvers resulted in better performance. For example, in the engine failure runs, various maneuvers were tried for turns similar to those in track-keeping runs: turns with 15° and 25° rudder, turns with hard right (35°) rudder, and turns up into the current. The ground tracks under each condition were compared to evaluate the relative efficacy of each. In addition, objective measures were used for evaluation of runs: deviation off-track (in the non-failure runs) and distance from land. Attention was also given to the lowest speeds over the ground attained to determine if a particular maneuver would make anchoring feasible.

TRACK-KEEPING RUNS.

Conclusions

Several conclusions can be drawn from the track-keeping study. Unless otherwise stated, the conclusions apply to the most severe tidal current conditions and an east/west wind of 40 knots.

1. All the vessels studied, which were fully laden and ranged from 40K DWT to 400K DWT, can satisfactorily transit each of the routes if they maintain an adequate speed through the water relative to existing environmental conditions.
2. Vessel size is not a primary variable affecting track-keeping capability; the 80K and 400K vessels held track about equally well. The ratio of rudder area to immersed profile area of the hull appears to be an important physical factor.

Runs	Vessels	Locations				Tugs			Wind			Current
(Type & Number)		Haro	Rosario	Bellingham	Admiralty	0	2	4	$270^o/40$	0	$090^o/40$	
Track-keeping 108	80K		✓			✓			✓		✓	Max. Ebb & Flood
	120K	✓	✓	✓	✓	✓			✓		✓	
	165K	✓	✓	✓		✓			✓		✓	
	280K	✓	✓	✓		✓			✓		✓	
	400K	✓	✓			✓			✓		✓	
Engine Failure 756	40K					✓			✓	✓	✓	6 knots head-on and following; also no current
	80K					✓			✓	✓	✓	
	120K					✓			✓	✓	✓	
	165K					✓			✓	✓	✓	
	280K					✓			✓	✓	✓	
Engine & Rudder Failure 1512	40K					✓	✓	✓	✓	✓	✓	Same as Engine Failure runs
	80K					✓	✓	✓	✓	✓	✓	
	120K					✓	✓	✓	✓	✓	✓	
	165K					✓	✓	✓	✓	✓	✓	
	280K					✓	✓	✓	✓	✓	✓	
Man-in-the-Loop: Track-Keeping 16	165K	✓	✓			✓					✓	Maximum Flood Current
Engine Failure 8	165K	✓				✓					✓	
Engine/Rudder Failure 8	165K	✓					✓				✓	
TOTAL 2408												

3. At the extreme conditions of 6 knots tidal current and an east/west wind of 40 knots, all vessels studied exhibited poor track-keeping ability at a speed through the water of 4 knots. At 6 knots speed through the water, considerable improvement was realized and this may be a satisfactory minimum speed for some vessels. At 8 knots, all vessels exhibited satisfactory track-keeping ability for these extreme conditions.
4. Very high crab angles are experienced at the high tidal current conditions when at low vessel speeds. Although the autopilot could cope with these conditions, they may be considered unacceptable by a human pilot. However, it is expected that a human pilot would periodically increase engine RPM without significantly increasing ship speed to achieve better control and to avoid large crab angles.
5. At high wind-to-ship speed ratios (about 10 to 1), quartering wind forces reach levels at which they can overpower the rudder. The effect of these wind forces is to dramatically increase the turn radius in directions opposite to the wind; e.g., left turns are difficult for winds on the starboard beam. Higher ship speeds not only improve ship controllability with respect to the wind but also make it easier to negotiate turns in high cross current.

<u>Recommendations</u>

1. Equilibrium rudder curves for various wind conditions are useful for predicting wind conditions at which vessel track-keeping capability becomes marginal. It is recommended that additional future research and development effort be expanded to develop accurate and meaningful static and dynamic response curves for various types of vessels. These data could be used by

masters or VTS personnel to determine whether it is safe to operate under specified conditions.

2. Additional research should be conducted on handling of vessels under various environmental conditions (current and wind) with the goal of defining a typical range or responses of human pilots. These data would be useful for defining off-line piloting algorithms.

OFF-LINE ENGINE FAILURE RUNS (RUDDER FULLY OPERABLE)

Conclusions

The following conclusions can be reached based on the off-line engine failure runs. The conclusions apply to conditions of 40-knot east or west winds and 6-knot head-on or following currents.

1. All of the vessels studied are highly susceptible to the wind at low speed. When engine failure occurred at 4 knots, and sometimes at 6 knots, the wind consistently overpowered the rudder and could turn the vessel in a direction opposite to that desired.
2. Following currents created the greatest difficulty for vessels. The current carried the vessel along while it was attempting (often unsuccessfully) to turn. Changes in course were impractical; very large advances occurred, and speed over the ground remained too high to attempt anchoring.
3. With a head-on current, the vessels also could not follow the desired course. However, the larger vessels, with their high inertia, were able to stem the current for appreciable periods of time before drifting helplessly backwards. By turning up into the current these vessels were also generally able to reduce their speed over the ground to speeds at which anchoring might be feasible (<0.5 knot). Varying the delay time before heading into the current demonstrated that increased

delay in the time at which the vessel is turned up into the current resulted in greater transfer and also reduced the amount of time at very low speeds over the ground available for anchoring. The larger the vessel, the longer the time delay it could tolerate before a turn-up-into-the-current became of little or no advantage.

4. The inability of all the vessels to consistently establish speeds over the ground at which anchoring may be attempted, and the difficulty of maintaining control in a turn, suggest that tug support is needed to guarantee safety in the event of engine failure.

ENGINE/RUDDER FAILURE RUNS

Conclusions

The following conclusions can be reached based on the off-line combined engine/rudder failure runs with tug assistance provided. The conclusions apply to 40-knot east or west winds.

1. The use of tugboats to retard the forward motion of the vessel results in an appreciable reduction in the distance traversed and the transfer in particular. In general, a significant benefit occurs with the application of the first two tugboats. The incremental improvement provided by two additional tugboats is not as great.
2. High magnitudes of transfer occur at ship speeds through the water of 8 knots or more. Tugboat utilization strategies other than pure retardation, which was the only strategy simulated, are required if lower transfers are to be achieved at these speeds.
3. At speeds through the water less than 8 knots, reasonable magnitudes of transfer can be achieved with retarding tugs. However, these lower speeds may conflict with

the requirements for satisfactory track-keeping when the extremes of current and wind exist.

Recommendations

1. Further analysis of the combined engine/rudder failure data should be carried out to determine whether tugboat utilization strategies, other than their use as pure decelerators, can bring the transfer values down to consistently safe values at 8 knots, or higher speeds through the water.
2. Research and development effort should be expended to create realistic models of tugboard usage that can be used in off-line studies. An interactive system with CRT display capabilities which permits study of tug techniques, should be considered.
3. The impact of the use of modern tugs, such as tractor tugs which can exert appreciable lateral forces at high speeds, should be studied.
4. Vessels should be equipped with speed-over-the-ground/through-the-water instrumentation (e.g., Doppler speed log) to help pilots and masters determine when feasible anchoring speeds are reached in emergency situations.

MANNED SIMULATION RUNS

Conclusions

Recalling the extreme environmental conditions under which all runs were made, the following conclusions can be drawn:

1. There were definite behavioral differences between 4- and 6-knot conditions. All test subjects regarded 4 knots of ship speed to be below the threshold for safe navigation under the extreme conditions that were simulated. It does not necessarily follow that 6 knots is a safe navigating speed.

2. Comparison of on-line and off-line track-keeping data suggests that a safe navigating speed might lie between 6 and 8 knots under these extreme conditions. This comparison also suggests the advisability of interpreting the off-line data conservatively; in some cases, the human did not perform as well as the autopilot.
3. There were definite and systematic behavioral differences between Puget Sound and New York Harbor pilots used as test subjects.

Recommendations

1. A greater number of runs with additional pilots should be made in the 4- to 8-knot ship speed range to identify the threshold for piloted controllability in a series of graduated, adverse environmental conditions.
2. A study of the training programs for various piloting organizations should be made. If it can be established that specific performance is more desirable (e.g., if more frequent rudder commands and radar bearings result in larger CPAs to points of land), then attempts should be made to stress such behavior in the pilot training programs.

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SECTION 1

BACKGROUND

The U.S.C.G. has been given the responsibility to investigate the need for regulations to govern the passage of oil tankers into the Puget Sound area. Such regulations may involve, for example:

- recommended safe maximum or minimum ship speeds under specified environmental conditions (wind, current)
- critical areas where special precautions may be required (tug escort, environmental or ship displacement tonnage constraints)
- the need for tugs
- procedures to be adopted in case of equipment failures.

Formulation of such regulations entails an investigation of the safety of passage of various sized tankers entering the Strait of Juan de Fuca and making their way by various channels to the oil terminals of the Puget Sound area (see Figure 1-1).

The terminals, and the routes by which they are to be approached, include:

<u>Cherry Point and Ferndale</u>

(a) North via Haro Strait

(b) North via Rosario Strait

<u>Anacortes</u>

(a) Rosario Strait and East Via Guemes Channel (ships under 45 ft. draft)

(b) Rosario Strait and North via Bellingham Channel around Guemes Island (ships over 45 ft. draft)

<u>Tacoma and Seattle</u>

(a) South via Admiralty Inlet into Puget Sound.

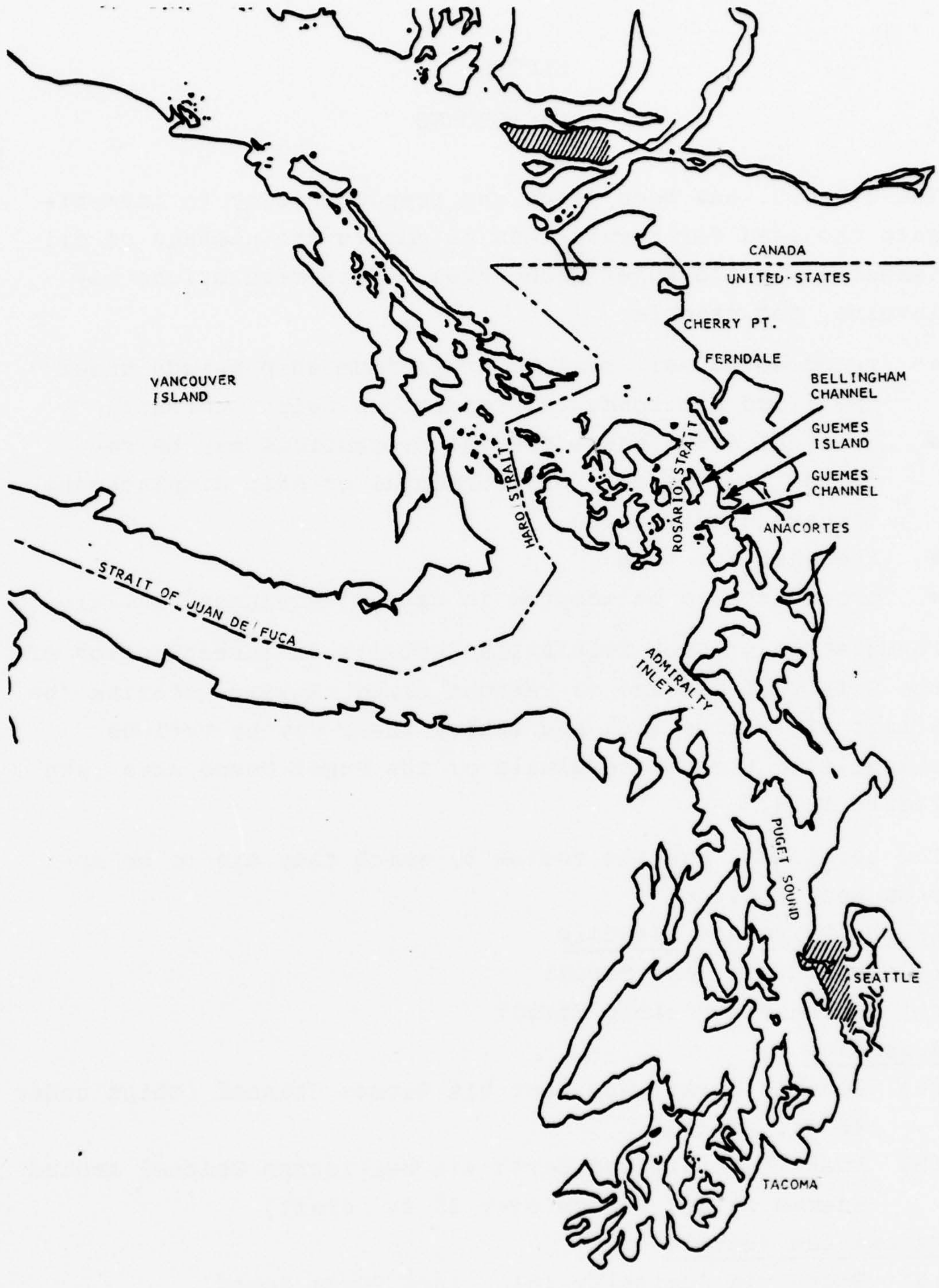

Figure 1-1. Area of Safety of Passage Study

The present study was designed along the guidelines proposed by the U.S.C.G. The purpose of the study was to acquire information needed to assess the safety of passage with

- no equipment failures, and
- equipment failures and tug support under maximum credible adverse environmental conditions.

Following an initial off-line (mathematical) investigation of the overall problem, additional studies of the critical areas were made on the CAORF simulator using Puget Sound and non-Puget Sound pilots, and a simulated radar image of the area with existing navaids. The CAORF runs were intended to provide a comparison between the results of the mathematical off-line study and the results of actual human behavior and to provide a sampling of realistic human behavior upon which any regulatory decisions might be based.

SECTION 2

EXPERIMENT DESCRIPTION AND TECHNICAL APPROACH

2.1 INTRODUCTION

There are two principal parts which comprise the overall Puget Sound investigation. They are:

- off-line runs
- on-line CAORF runs.

By "off-line runs" is meant a series of problem investigations by means of a digital computer using a mathematical model of ship dynamics and an appropriate autopilot to steer the vessel. The results of such investigations shed light on the nature of ship handling difficulties and the most promising means of coping with these difficulties. Off-line runs have the advantage of being relatively fast and inexpensive. They provide the basis for isolating problem areas requiring additional in-depth analysis.

By "on-line CAORF runs" is meant a series of experiments conducted on the CAORF ship maneuvering simulator with actual ship pilots operating in real-time. For a description of the CAORF simulator, see Appendix C.

Two fundamental types of problems were considered in the Puget Sound project. They are:

- track-keeping problems
- failed-equipment problems.

Track-keeping runs (in both the on-line and off-line mode) involve navigation of various sized tankers along selected routes with all equipment functioning normally under selected maximum credible adverse environmental conditions. The philosophy underlying this methodology was that if ship navigation can be performed adequately under the most

extreme conditions, it can also be done under all less severe conditions. Those conditions under which navigation is found to be more difficult may be considered for further investigation and possible regulation.

Failed equipment runs (in both the on-line and off-line mode) involve an investigation of performance under maximum credible environmental conditions and with various equipment failures. The identification of dangerous or unacceptable performance suggests preventive measures, operating procedures or necessary equipment redundancy to minimize the occurrence of such performance. Of the possible equipment failure conditions which might occur, the U.S.C.G. has chosen to investigate the cases of

- failed engine (rudder still working)
- failed engine/steering combined.

2.2 OFF-LINE TRACK-KEEPING RUNS

This portion of the study involved the navigation of five (5) different-sized, fully loaded tankers along four (4) different routes under realistic maximum credible adverse environmental conditions and with all equipment functioning normally (see Table 2-1). The tankers used were:

- 80,000 DWT (referred to as the 80K tanker)
- 120,000 DWT
- 165,000 DWT
- 280,000 DWT
- 400,000 DWT.

The physical description of these ships as well as turning circle data may be found in Appendix B.

The routes which the tankers had to navigate are shown in Figure 2-1 through 2-4. The track lines to be followed in each case are also shown. The number of routes for each ship type is different since the larger ships are subject to draft restrictions.

TABLE 2-1. OFF-LINE TRACK-KEEPING RUNS

Ship Type (DWT)	Routes	Wind Condition	Current	Ship Speed Through the Water	No. of Runs
80K	1	270°/40 & 090°/40	Maximum Ebb and Flood	See Note Below	12
120K	1,2,3,4				32
165K	1,2,3				24
280K	1,2,3				24
400K	1,2				16
				TOTAL:	108

ROUTES

1 - Rosario Strait
2 - Haro Strait
3 - Bellingham Channel
4 - Tacoma via Admiralty Inlet

NOTE: Ship speed is current-dependent:
for ebb tide current (head-on): 10 knots
for flood tide current (following): 4,6,8 knots

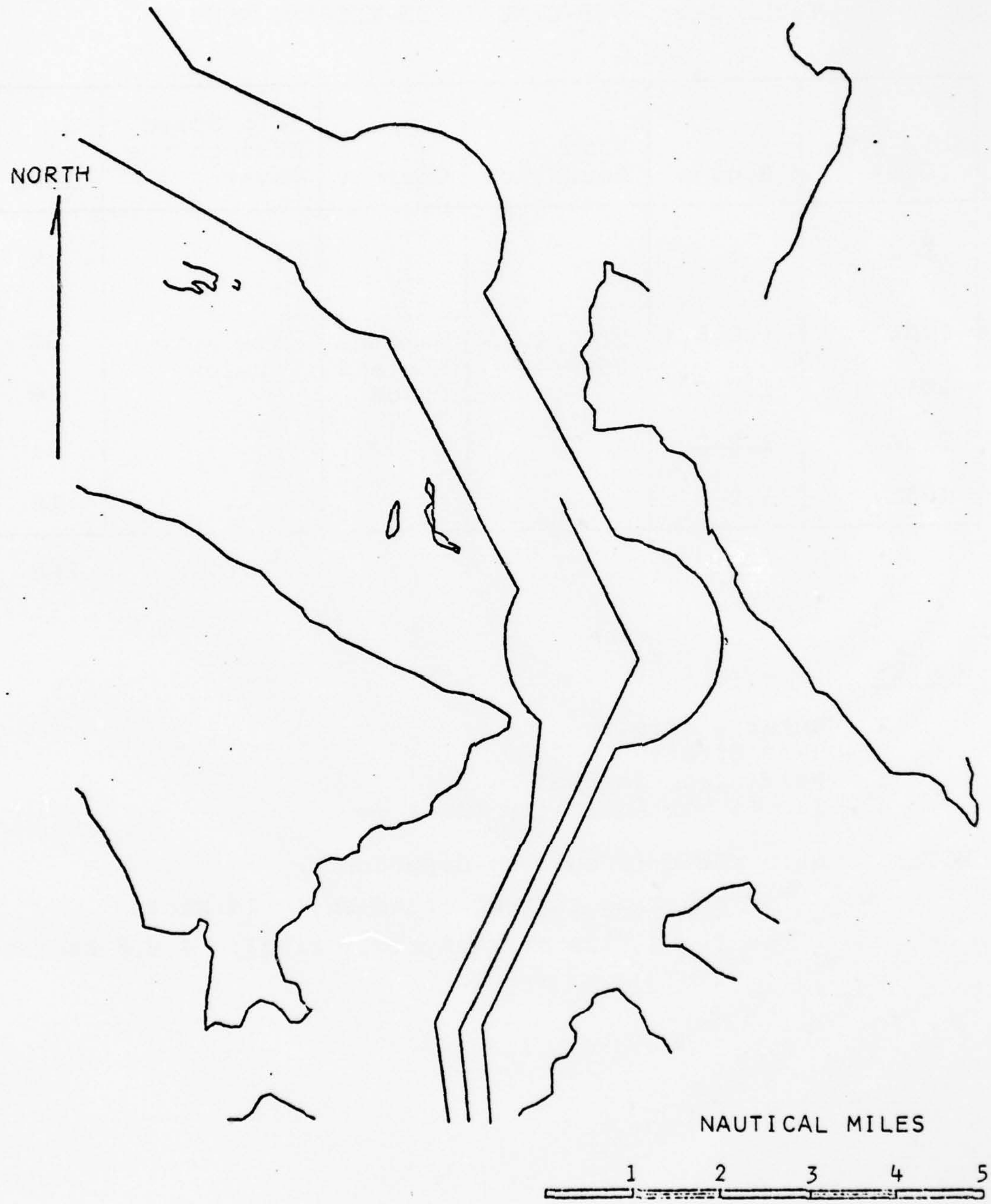

Figure 2-1. Rosario Strait

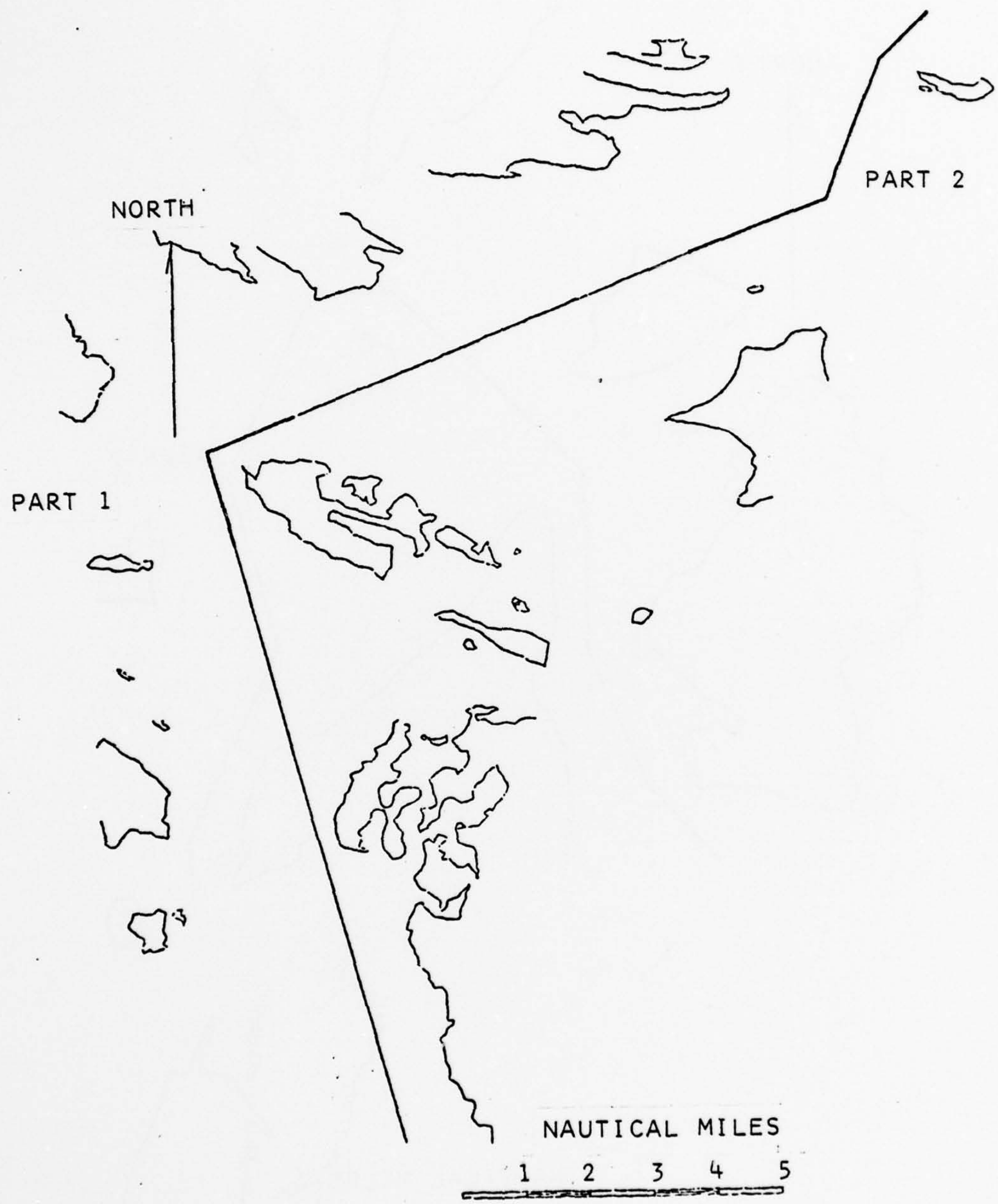

Figure 2-2. Haro Strait

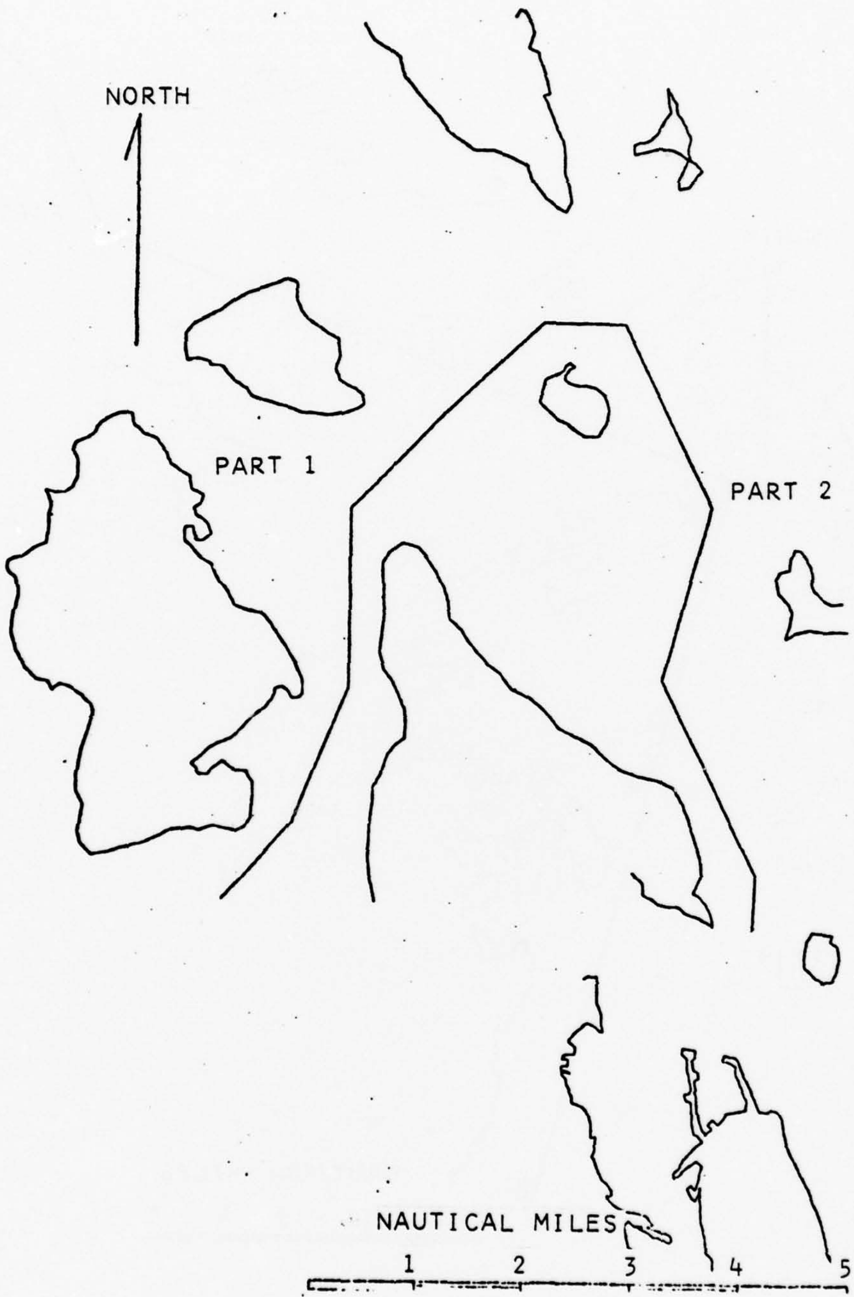

Figure 2-3. Bellingham Channel

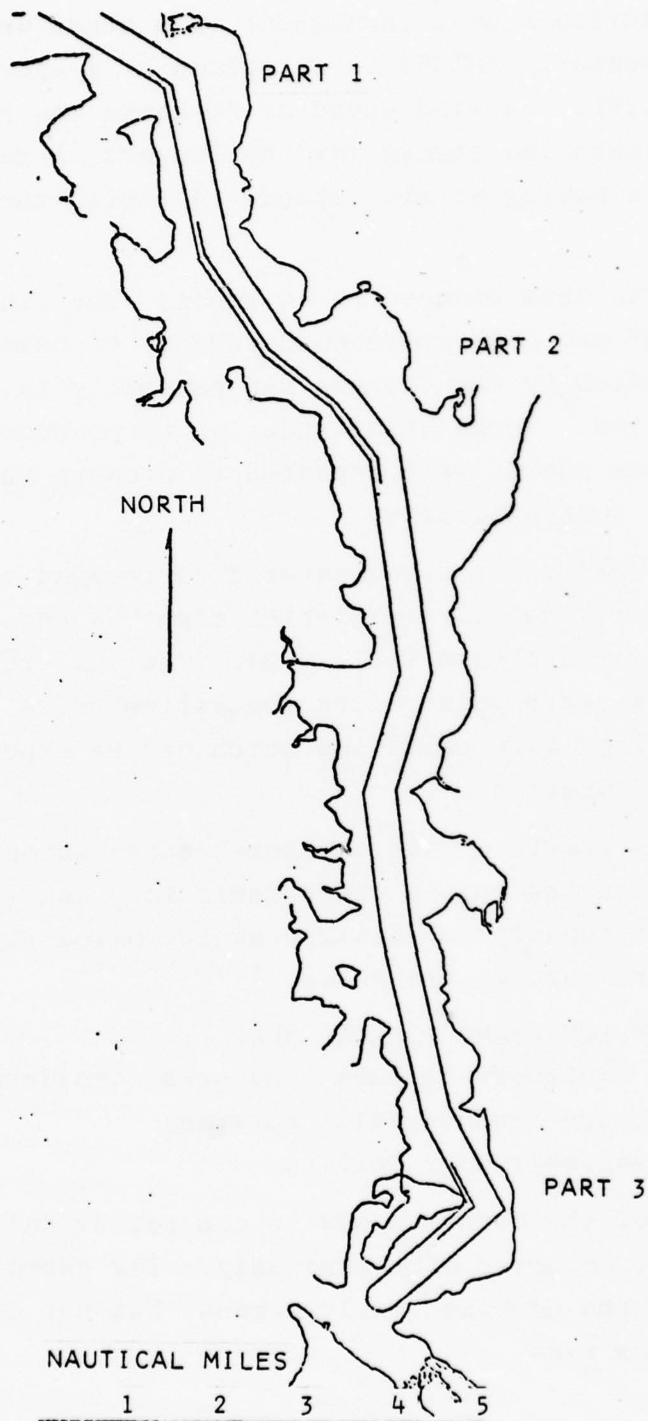

Figure 2-4. Tacoma Via Admiralty Inlet

The wind conditions used throughout this study were easterly (090°) and westerly (270°) in direction at a speed of 40 knots. Initially, a wind speed of 50 knots was tried, but found to be much too strong for the tankers to maintain control while moving at slow speeds (4 knots) through the water.

Wind speed was thus reduced to 40 knots. The wind directions of 270° and 090° correspond roughly to beam since the routes navigated by the tankers run generally in a north-south direction. These beam winds, which produce a maximum set toward the shore, were expected to produce the greatest test of ship controllability.

The water currents to be encountered correspond to the maximum ebb or flood currents which might be encountered along a given route (see Table 2-2). That is, the ship encountered at each point along the entire route the maximum ebb or flood tide condition which may be expected along the route in question.

Each ship was provided with a track-keeping autopilot, adjusted to match the ship's characteristics, and ship RPM was adjusted continuously to maintain an approximately constant fore/aft speed through the water.

2.3 OFF-LINE EQUIPMENT FAILURE RUNS

Two types of equipment failure runs were considered:

- Engine failure (rudder still working)
- Combined engine/rudder failure.

In the case of the combined engine and rudder failure runs, both failures occurred simultaneously. Tug support was available in the combined failure runs, but not in the engine failure runs.

TABLE 2-2. MAXIMUM EBB AND FLOOD CURRENTS

Route	Maximum Ebb (direction/ speed (kts))*	Maximum Flood (direction/ speed (kts))*
Rosario Strait	$200^{o}/4.8$	$020^{o}/3.8$
Haro Strait		
Part 1	$260^{o}/3.0$	$080^{o}/2.0$
Part 2	$225^{o}/6.0$	$050^{o}/4.5$
Admiralty Inlet		
Part 1	$300^{o}/6.0$	$125^{o}/7.5$
Part 2	$350^{o}/5.0$	$155^{o}/4.5$
Part 3	$000^{o}/1.0$	$180^{o}/1.0$
Bellingham Channel		
Part 1	$190^{o}/4.5$	$045^{o}/4.0$
Part 2	$240^{o}/2.0$	$310^{o}/1.5$

*Direction in which current flows.

2.3.1 Off-Line Engine Failure (no tugs available)

The situation hypothesized is the following:

A ship is navigating a channel in the presence of wind and current. Just as a turn is to be initiated, an engine failure occurs and the ship begins to loose speed. There are several questions requiring answers:

- Can the ship, with reduced rudder effectiveness, complete the intended turn?
- Can the ship remain in the channel and maintain control, and how long can it do so?
- Will the ship reduce its speed over the ground sufficiently to enable it to anchor?

The summary of conditions studied is contained in Table 2-3.

The ship sizes to be run here include the addition of a 40,000 DWT tanker. The 40K ship was not utilized in the track-keeping portion of the study since there was no serious question as to its track-keeping ability. Due to technical difficulties, results of engine failure runs made with the 400K tanker were not available for this report and will be delivered later under separate cover.

The water currents used were following currents at 6 knots (+6), head-on currents at 6 knots (-6) and no current (0). The constant directions chosen resulted in currents that were initially either head-on or following. The tidal current speeds represent the approximate maximum credible speeds encountered in the Puget Sound area.

The wind conditions were chosen for the same reasons given previously, with the inclusion here of a no-wind condition (zero-wind).

The magnitude of the turns to be attempted were 30^{o}, 60^{o}, and 90^{o} to the right. Consideration of symmetry provides the equivalent information for left turns since any bias due to propulsion is not present with the engine failed.

TABLE 2-3. OFF-LINE ENGINE FAILURE RUNS

Ship Type (DWT)	Ship Speed Thru Water (kts)	Water Current Speed (kts)*	Wind Condition	Magnitude of Right Turn	Magnitude of Rudder	No. of Runs
40K 80K 120K 165K 280K 400K	See Note Below	6,0,-6	270^{o} @ 40 kts and 090^{o} @ 40 kts zero wind	$30^{o}, 60^{o}, 90^{o}$	$15^{o}, 25^{o}$	126 for each ship type

TOTAL 756

Note: with no current (0) or a following (+6) current, ship speeds are 4,6, and 8 knots; with a head on (-6) current, ship speed is 10 knots.

* negative current is a head-on current
positive current is a following current

Under each of the various conditions listed in Table 2-3, the turn was initiated with a right rudder deflection of either 15° or 25°. When 50% of the turn had been completed, control was turned over to an autopilot to steady up on the new heading. The choice of 15° and 25° rudder represented an attempt to evaluate two different pilot preferences toward quickness of turns. The ships were unable to make reasonable turns using the heading sensing autopilot, and therefore additional runs were made with a combination ground-track/heading sensing autopilot. These runs will be described in a subsequent section.

2.3.2 Off-Line Combined Engine/Rudder Failure (tugs avail-available)

The basic question here is whether or not the application of tugs can prevent the grounding of a tanker which has suffered the simultaneous loss of both engine and rudder. The conditions under which the runs were made are summarized in Table 2-4. Again, due to technical difficulties, results made with 400K tanker will be delivered later under separate cover.

The use of tugs in this off-line program was simulated in the following way. The tugs were regarded as accompanying the ship and already attached by lines. That is, the tugs already had a line on the tanker but were applying no retarding force until called upon to do so (see Figure 2-5). There was an assumed 60-second delay after the occurrence of the simultaneous equipment failures to simulate the time required for the bridge crew to become alerted and ask for tug assistance. An additional 30-second delay was imposed to simulate the time required for the tugs to begin backing (see Figure 2-6). Thus a total delay of 90 seconds was imposed from time of failure until tugs were backing. In view of the rich variety of tug procedures which might be

TABLE 2-4. OFF-LINE COMBINED RUDDER/ENGINE FAILURE RUNS

Ship Type Ship Type	Ship Speed Thru Water (kts)	Water Current Speeds (kts)	Wind Condition	Rudder Angle After Failure	Tug Support	No. of Runs
40K DWT 80K DWT 120K DWT 165K DWT 280K DWT 400K DWT	See Note Below	6,0,-6	270^{o} @ 40kts, 090^{o} @ 40 kts, zero wind	$0^{o}, 15^{o}, 25^{o}$ 35^{o}	0,2 or 4 tugs	252

TOTAL 1512

* Three runs per ship type utilizing simplified "rudder tug" dynamics to investigate potential effects

Note: Ship speed and tug usage are to be current-dependent:

Zero current or 6 knot following current: ship speeds of 4,6 and 8 knots with and without tugs

-6 knot head-on current: with and without tugs, ship speed of 10 knots

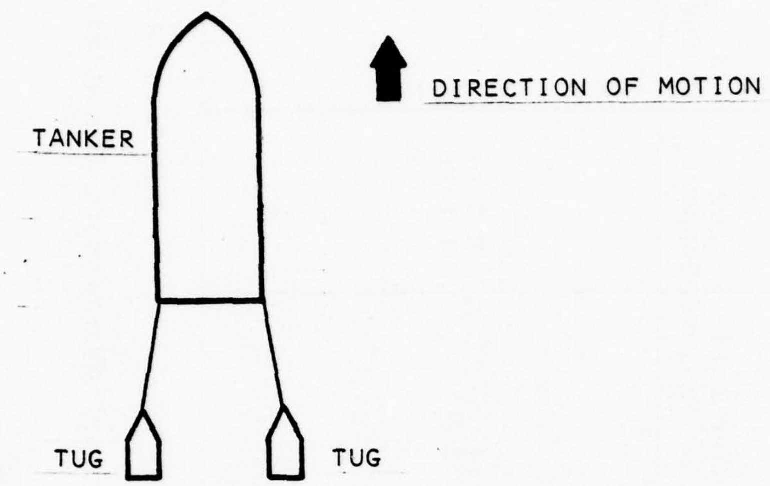

Figure 2-5. Tugs Accompanying Ship on Lines

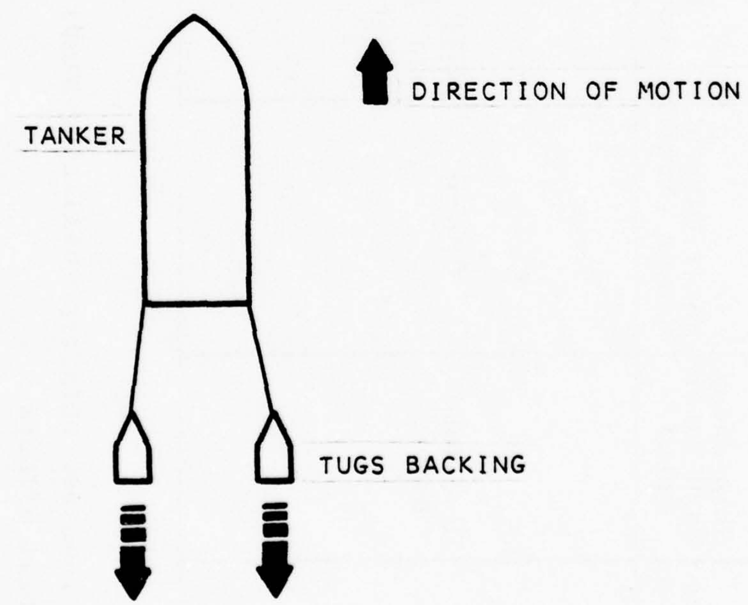

Figure 2-6. Tugs in Position and Backing

implemented in the real world (steering tugs, differential backing tugs, etc.) and the relative difficulty of doing so off-line, backing tugs were the only type permitted. All tugs were required to back full and exerted only a retarding or drag force on the tanker.

Thus, all resultant tug forces were represented as a vector force operating on the tanker's center of gravity and oriented in a direction opposite to the tanker's heading. The number of tugs available was either 0, 2, or 4. In the event that 4 tugs were used, 2 were regarded as made up on lines at the bow, and 2 trailing the stern of the tanker. Further references to tug pulling forces may be found in Appendix A.

The rudder was allowed to fail in positions corresponding to 0°, 15°, 25°, and 35° right rudder to cover the range of all possible failure positions.

2.4 CAORF MAN-IN-THE-LOOP RUNS

One week of CAORF simulation time was dedicated to accomplishing man-in-the-loop runs. These runs were basically normal track-keeping and failed equipment runs in the areas of Haro Strait and Rosario Strait. Four pilots (test subjects) were chosen to utilize their experience and knowledge to accomplish the prescribed runs. The purpose of these runs was to provide data on human shiphandling capabilities under some of the conditions simulated for the off-line runs in order to permit judgment of the validity of the off-line runs.

2.4.1 Test Subjects

All of the test subjects who took part in the man-in-the-loop runs were practicing professional pilots. Two were from the Puget Sound Pilots' Association. They were selected from a list of names provided by the U.S.C.G. The remaining two pilots were from the United New York Sandy

Hook Pilot's Association. Neither of the New York pilots had experience piloting in the Puget Sound area and were selected because of their length of experience and because they were qualified to pilot large vessels. Table 2-5 summarizes their experience.

2.4.2 Familiarization Training

Each test subject was provided with familiarization training prior to the commencement of the experimental runs. Upon arrival, each test subject was given an introductory briefing and tour of the facility. Subsequently, they were provided with approximately five hours of maneuvering training on the simulator. This maneuvering training included:

- bridge equipment familiarization, and
- ship handling training.

During the ship handling training, the test subjects were required to:

- steer through a giant slalom (zig-zag) course composed of a buoy and stationary ships, and perform a crash stop maneuver (see Figure 2-7)
- negotiate Bellingham Channel (see Figure 2-8) at low speeds with ½-mile visibility and utilize the CAORF tugs to slow the ship's fore/aft speed as a preparation for the actual runs.

The purpose of the above was to acquaint the pilots with the ship's handling qualities, give them experience maneuvering the modeled ship at low speed, utilize the tugs as implemented in CAORF and acclimate them to the simulator and those assisting in running the bridge (helmsman and mate) and the experiment procedures.

2.4.3 Ownship Performance Characteristics

The tanker model chosen for use during the man-in-the-loop exercises was the 165,000 DWT ship since it approximates in

TABLE 2-5. SUMMARY OF TEST SUBJECT EXPERIENCE

Test Subject	Age	No. of Years Experience Piloting	Largest Vessel Piloted
1	48	26	125,000 DWT
2	50	26	250,000 DWT
3	51	12	160,000 DWT
4	69	33	125,000 DWT

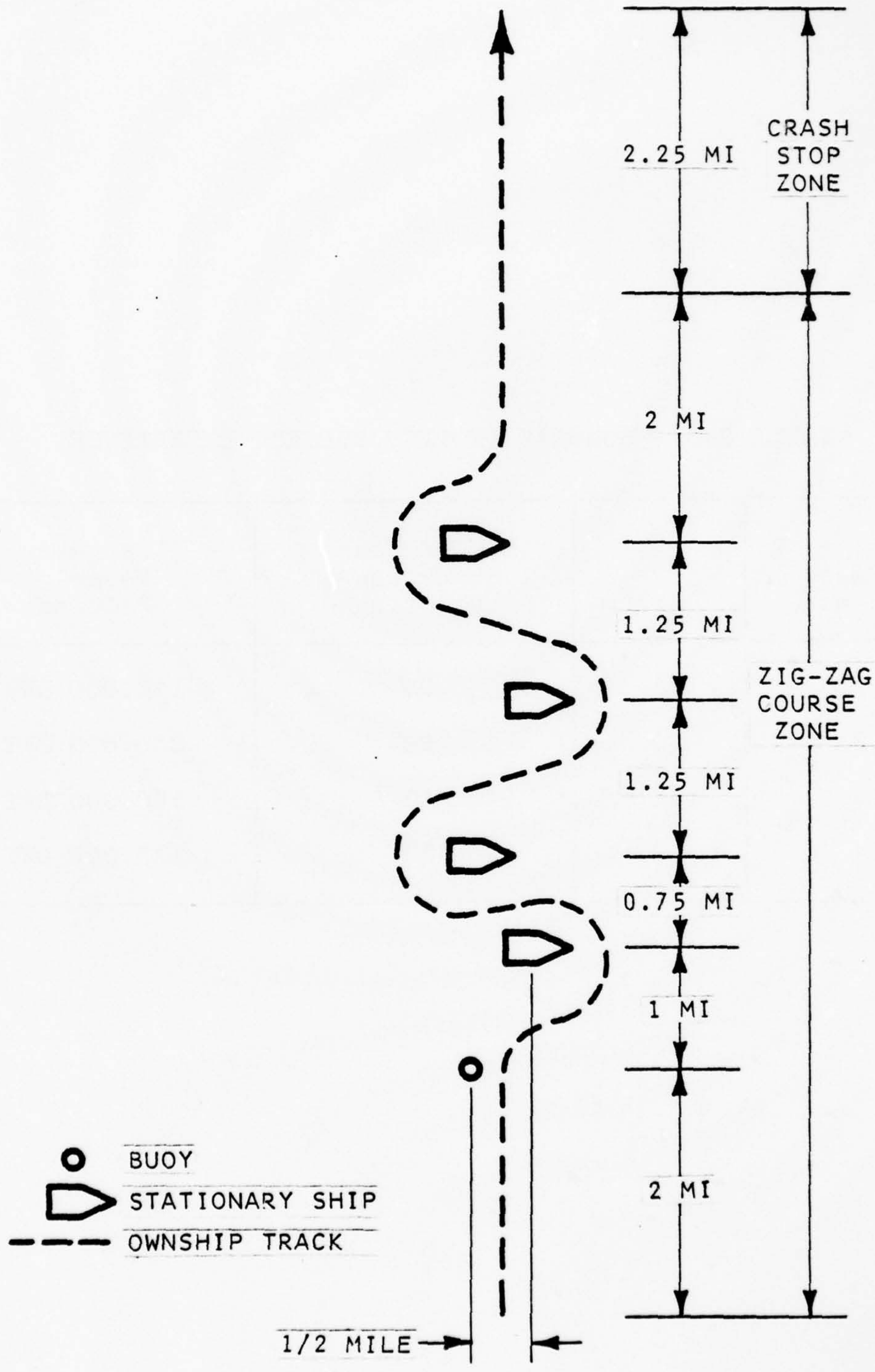

Figure 2-7. Slalom Zig-Zag Course

Figure 2-8. Bellingham Channel Familiarization Runs.

size the largest ships that are expected to enter Puget Sound area during the next several years. The tankers were simulated with the following characteristics:

Length (B.P.)	951	ft.
Draft (loaded)	52	ft.
Beam	155.4	ft.
Displacement, long tons	180,550	
Rudder Area	741.8	sq. ft.
Rudder Movable Area	634.2	sq. ft.
Propeller Diameter	26	ft.
RPM/Knot	6.29	
Ahead H.P.	29,000	
Maximum Rudder Angle	35	degrees

These characteristics plus unique parameters of the ship such as hydrodynamic, inertial, propulsion, rudder, aerodynamic, and engine coefficients were entered into a computer program, which resulted in realistic and accurate motion of the simulated ship. Thus the vessel appeared to move through the simulated scene in a realistic fashion.

2.4.4 Experimental Design

A total of eight experimental runs, each approximately one hour in duration, was planned for each of the four test subjects. Four of these runs were designed as track-keeping runs and four as failed-equipment runs. The scenarios are defined in Table 2-6 and the sequence of runs for each test subject is defined in Table 2-7. All runs were performed in limited visibility (½ mile) and utilizing a simulated radar presentation of the area.

The variable of primary interest in all cases was that of ship speed. It was considered of great importance to gain some insight into the threshold of piloted ship controllability and determine that speed through the water below

TABLE 2-6. SCENARIOS DEFINED

Ship Speed	Track-Keeping Runs Location		Failed-Equipment Runs Failure	
	Rosario	Haro	Rudder & Engine[1]	Engine[2]
4kts	1[3]	2	5	6
6kts	3	4	7	8

[1]Two tugs available; 1.0 minute delay

[2]No tugs available

[3]All entries represent scenario number in the total set of eight scenarios

TABLE 2-7. SCENARIO RUN ORDER

Subject	Sequence of Scenarios							
1	2	6	5	3	8	4	1	7
2	8	1	2	7	3	6	5	4
3	7	4	1	6	2	5	8	3
4	3	5	8	4	7	1	2	6

which controllability becomes difficult. Test subjects were required to navigate the ship through the designated areas in Rosario Strait and Haro Strait, at speeds of 4 and 6 knots. The pilots were required to maintain the ship speed through the water to within a 0.5 knot tolerance. They were, however, permitted to increase RPMs for brief periods to increase rudder effectiveness but with little or no increase in speed. The environmental conditions were those of an easterly wind (090°) at 40 knots and the maximum flood tide as listed in Table 2-2 earlier in this report.

2.5 SHIP HYDRODYNAMICS AND AERODYNAMICS

2.5.1 Equations of Motion

The motion of a ship in the horizontal plane, with the coupling effects of roll, pitch and heave motions on the horizontal motion assumed to be negligible, can be described by the following set of equations for surge, sway and yaw.

SURGE: $$M(\dot{u} - rv) = \underset{\text{(Hull)}}{X_{HYDRO}} + X_{RUDDER} + X_{PROP} + X_{WIND} + X_{EXT}$$

SWAY: $$M(\dot{v} + ru) = \underset{\text{(Hull)}}{Y_{HYDRO}} + Y_{RUDDER} + Y_{PROP} + Y_{WIND} + Y_{EXT}$$

YAW: $$I_z\dot{r} = \underset{\text{(Hull)}}{N_{HYDRO}} + N_{RUDDER} + N_{PROP} + N_{WIND} + N_{EXT}$$

The terms on the right-hand side of these equations are hydrodynamic forces and moments resulting from distributed pressures on ship's hull, the rudder and propeller, in addition to external non-hydrodynamics effects such as wind, tugs, etc. The terms u and v are fore/aft and athwartship velocities respectively, along and normal to ship's centerline. r is the rotational rate of the ship; M the mass in slugs; and I_z the moment of inertia about vertical axis through the center-of-gravity.

The hydrodynamic forces and moments can be expressed as functions of u, v, r and δ and their derivatives, and can be expanded in Taylor series about the instantaneous state of motion. The coefficients of this Taylor expansion are hydrodynamic derivatives that must be determined from scaled towing tank tests, sea trials and/or theoretically.

The propulsive forces and moments can be expressed in terms of fore and aft ship speed (u) and propeller revolutions (n). For example:

$$X_{PROP} = C_{11}u^2 + C_{12}un + C_{13}n^2$$

$$Y_{PROP} = B_{11}u^2 + B_{12}un + B_{13}n^2$$

$$N_{PROP} = A_{11}u^2 + A_{12}un + A_{13}n^2$$

In forward motion and clockwise rotation of propeller ($u > 0$, $n > 0$), Y_{PROP} AND N_{PROP} are both set equal to zero. Different values of the A, B, C coefficients must be assigned to describe forces and moments for the various combinations of direction of ship motion and propeller rotation.

The final form of equations of surge, sway and yaw become:

$$M(\dot{u} - rv) = \tfrac{1}{2}\rho\left[c_0L^2U^2 + c_1vrL^3 + c_2L^2r^2 + c_3K_RL^2U^2\delta^2\right] + (c_{11}u^2 + c_{12}un + c_{13}n^2) + X_{WIND} + X_{EXT}$$

$$M(\dot{v} + ru) = \tfrac{1}{2}\rho\left[b_0L^2U^2 + b_1L^2Uv + b_2vL^3U + b_3K_RL^2U^2\delta + b_5\frac{L}{U}^3v^2r + b_6\frac{L}{U}^4vr^2 + b_7\frac{L}{U}^2v^3 + b_8\frac{L}{U}^5r^3 + b_9K_RL^2U^2\delta^3\right] + Y_{WIND} + Y_{EXT}$$

$$I_z\dot{r} = \tfrac{1}{2}\rho\left[a_0L^3U^2 + a_1L^3Uv + a_1L^3Uv + a_2UL^4r + a_3K_RL^3U^2\delta + a_5\frac{L}{U_2}^4v^2r + a_6\frac{L}{U}^5vr^2 + a_7\frac{L}{U}^3v^3 + a_8\frac{L}{U}^6r^3 + a_9K_RU^2L^3\delta^3 + N_{WIND} + N_{EXT}\right.$$

The coefficients (derivatives) a, b, c are available from model tests, and other sources, for each particular ship.

These three equations are solved simultaneously for u, v, and r as functions of time, and from these values the instantaneous position of the ship, its heading and its trackline are derived to completely describe the ship's trajectory.

The value of U is resultant ship speed through the water $=\sqrt{u^2 + v^2}$. The value of $\frac{1}{2}\rho$ for water is approximately unity. K_R represents a rudder-propeller interaction (that is, ship speed, propeller RPM, etc.)

2.5.2 Initialization

In order to maintain a predetermined straight course in wind, a certain magnitude of rudder angle is required to counteract the hydrodynamic and aerodynamic forces and moments. The rudder angle is a function of ship speed, heading and the speed and direction of the wind. All of the track-keeping and equipment failure runs started with the rudder angle and the corresponding slip angle needed to maintain the ship approximately on the given course. The propeller RPM was set to maintain the speed through the water at the desired level.

2.5.3 Rudder Effectiveness

The effectiveness of the rudder depends upon the resultant speed of water flowing over the rudder, situated aft of the propeller. This flow is due to the combined effect of water flow in the ship's wake due to its forward motion and also to the additional flow from propeller wash over the rudder. At low ship speeds, the propeller wash effect becomes predominant, and accounts for the effectiveness of the so-called "kick maneuver" at low speeds, or at rest.

The rudder effectiveness assumed in the off-line studies considered an empirical formulation previously used by Eda and derived from the Japanese literature. This related (through a multiplier K_R) the rudder force and moment coefficients at any particular combination of fore/aft speed and engine revolutions to the corresponding coefficients under equilibrium conditions, $a = K_R a_e$.

K_R is related to the effective slip ratio, S, by

$$K_R = \frac{1 + kS^{1.5}}{1 + kS_e^{1.5}}$$

with $k = 7$ and $S = 1 - ({}^{u}/_{pn})$
(p = pitch)

As an example of the application of this formula, consider the rudder effectiveness after an engine failure has occurred, and the propeller is windmilling. In the next section it is shown that windmilling conditions for an 80,000 DWT tanker occur with

$\frac{n_w}{u_w} = \frac{1}{30}$ (n_w = RPS, u_w = fps), (subscript "w" refers to windmilling). The corresponding equilibrium value is

$\frac{n_e}{u} = \frac{1}{15}$.

As a result, $\frac{u_e}{n_e p} = \frac{1}{2}(\frac{u_w}{n_w p})$. With a pitch = 18' $\frac{u_e}{n_e p} = \frac{17}{18}$,

$S_e = .055$. However, $\frac{u_w}{n_w p} = \frac{34}{18} > 1$, hence $S < 0$. For values of $S < 0$, a value of $S = 0$ must be inserted in the K_R formula.

$$\therefore K_R = \frac{1}{1 + 7(.055)^{1.5}} = \frac{1}{1.090} = .917$$

or the rudder effectiveness is 92% of its value under equilibrium conditions. For a locked propeller, n = 0 and

$S < 0$. Since $S = 0$ is inserted (under these conditions) into K_R, K_R for the locked propeller will also equal 92%.

2.5.4 Propeller Drag

Two cases were considered:

(1) Propeller locked ($n = 0$)

and

(2) Propeller windmilling (torque $Q = 0$)

Case 1 Locked Propeller

The thrust $T = c_{11}u^2 + c_{12}un + c_{13}n^2$, and when $n = 0$,

$$T = c_{11}u^2.$$

For all ships considered, c_{11} is negative and, consequently, the thrust is negative, indicating a drag due to the locked propeller. For the 80,000 DWT tanker, this value is $-57.32u^2$ (u in feet/sec).

Case 2

For $^P/_D = 0.8$ and, using typical thrust and torque characteristic curves, we find that when $J = \frac{V_A}{nD} = 1.013$, the torque $Q = 0$ and corresponding thrust coefficient $K_T = -.05$. Using an appropriate wake factor, $w = 0.25$ ($V_A = u(1 - w)$), $D = 23'$ and $p = 18.4'$, these yield $\frac{n}{u} = \frac{1}{30}$, where n = RPS and u = fps.

The corresponding thrust when $Q = 0$ ($J = 1.013$, $k_T = -.05$) is $T = K_t \rho n^2 D^4 = -29.12u^2$

This indicates that the drag of the windmilling propeller is very closely one-half the corresponding value of the locked propeller.

Off-line calculations were performed with different values of propeller drag ranging from a maximum corresponding to the locked propeller to a zero value to determine the influence of propeller drag on the turning trajectory. The results (Figure 2-9) indicated only a slight variation, typically

on the order of ½%. Thus, for our purposes, the assumption of a locked propeller introduces only a negligible error.

2.5.5 Computation of Tug Forces

This section contains a description of the use of tug forces in both the on-line and off-line portions of this study. In addition, Appendix A contains the reference material submitted by C.R. Horton, an acknowledged expert on the use of tugs. This material was considered in the computation of realistic astern pulling forces of tugs.

2.5.5.1 Tug Forces Off-Line

Figure 2-10 is a graph of tug pulling power as a function of ship speed through the water for several different types of tug boats. Of those listed, only the Open Screw and Controllable Pitch (C.P.) types are available in Puget Sound at this time. To be conservative, the curve corresponding to the C.P. type was selected as representing a credible minimum power case. In addition, since the astern pulling power is nearly constant over our range of interest (0 to 6 knots), a decision was made to use 14 pounds per shaft horsepower as a credible, but conservative, estimate of the maximum astern pull of the tugs to be implemented. As indicated in Mr. Horton's submission, it is necessary to use 80% of this value as the actual pulling power. For the 5,000 and 7,200 horsepower tugs available in Puget Sound, these actual pulling figures become:

7,200 H.P. Tugs: $(7{,}200) \times (14) \times (0.8) = 80{,}640 \simeq 80{,}000$ lbs.
5,000 H.P. Tugs: $(5{,}000) \times (14) \times (0.8) = 56{,}000$ lbs.

Thus, all tugs used in the off-line runs were required to pull full astern with forces of either 56,000 lbs. or 80,000 lbs. For the 30K, 80K and 120K tankers, 5,000 HP tugs were used; for the 165K and 280K tankers, 7,200 HP tugs were used.

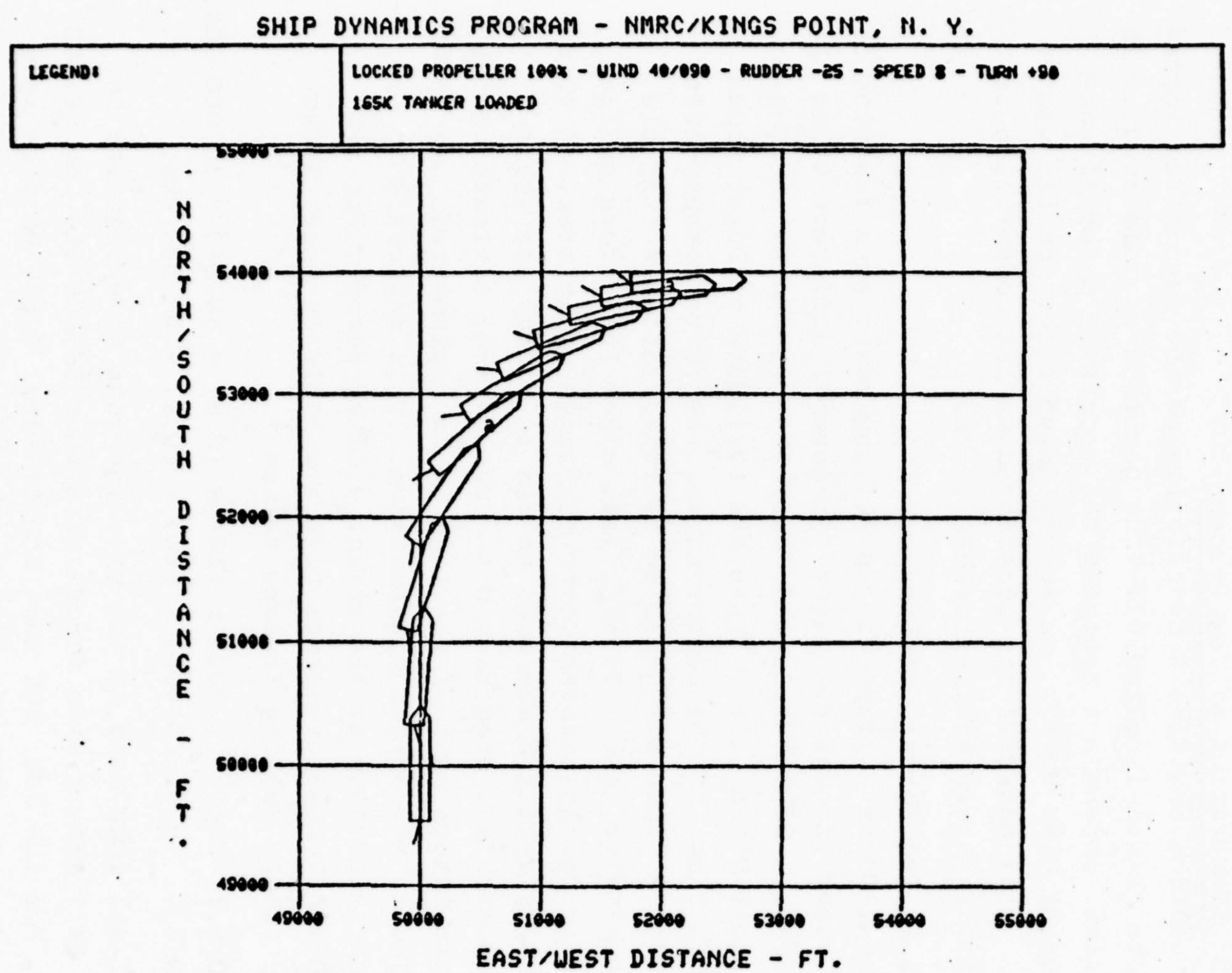

Figure 2-9. Propeller Drag Comparisons (Part 1)

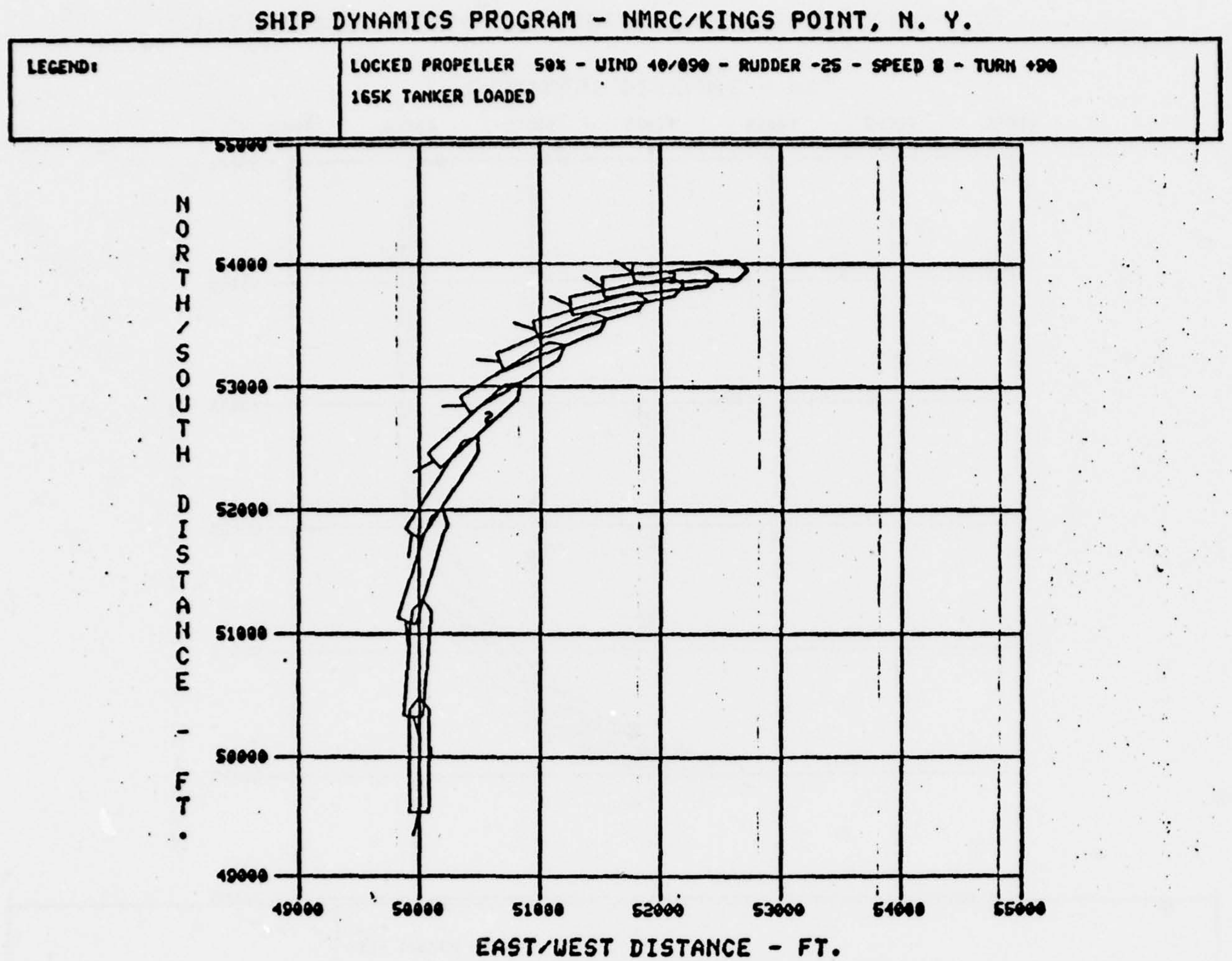

Figure 2-9. Propeller Drag Comparisons (Part 2)

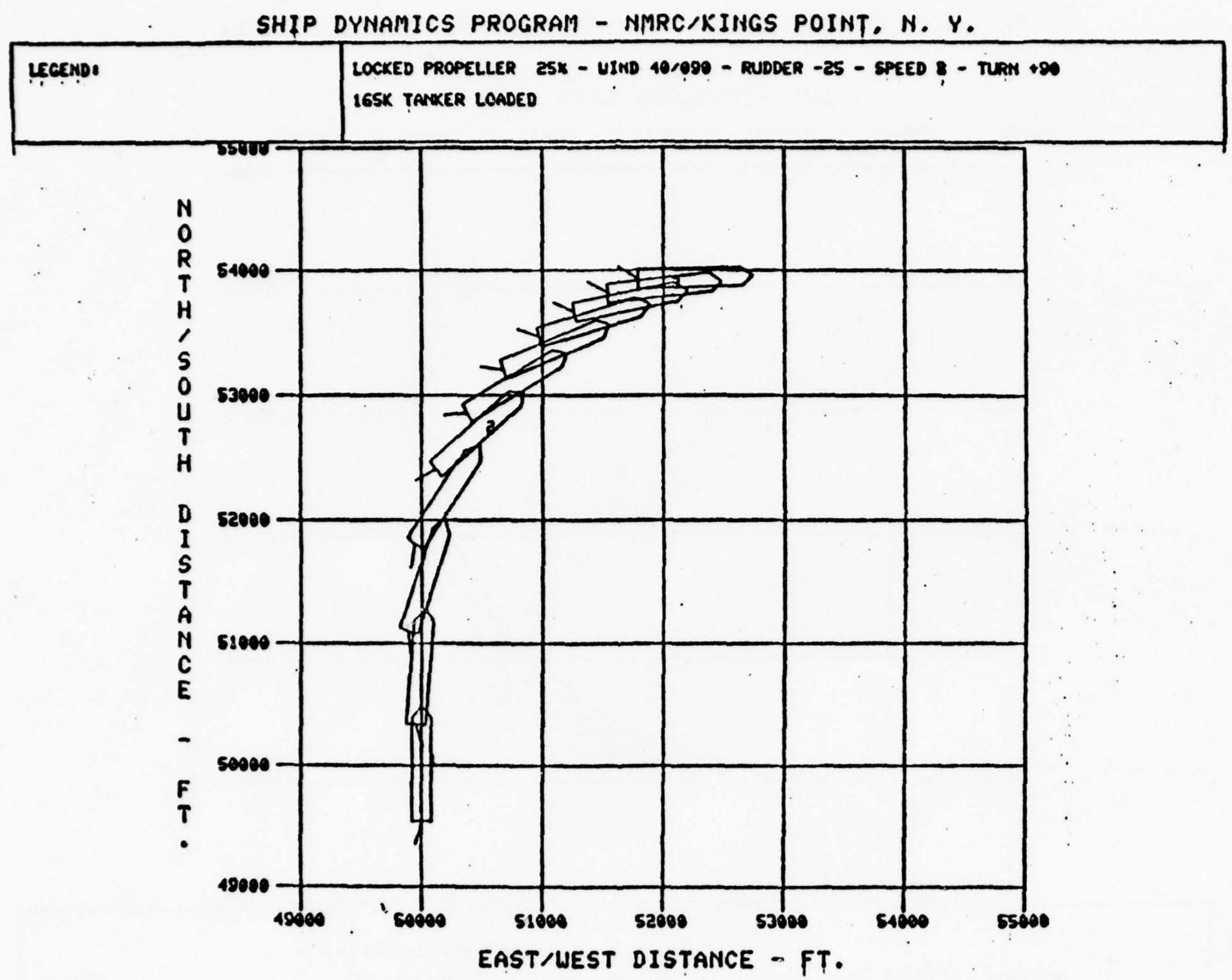

Figure 2-9. Propeller Drag Comparisons (Part 3)

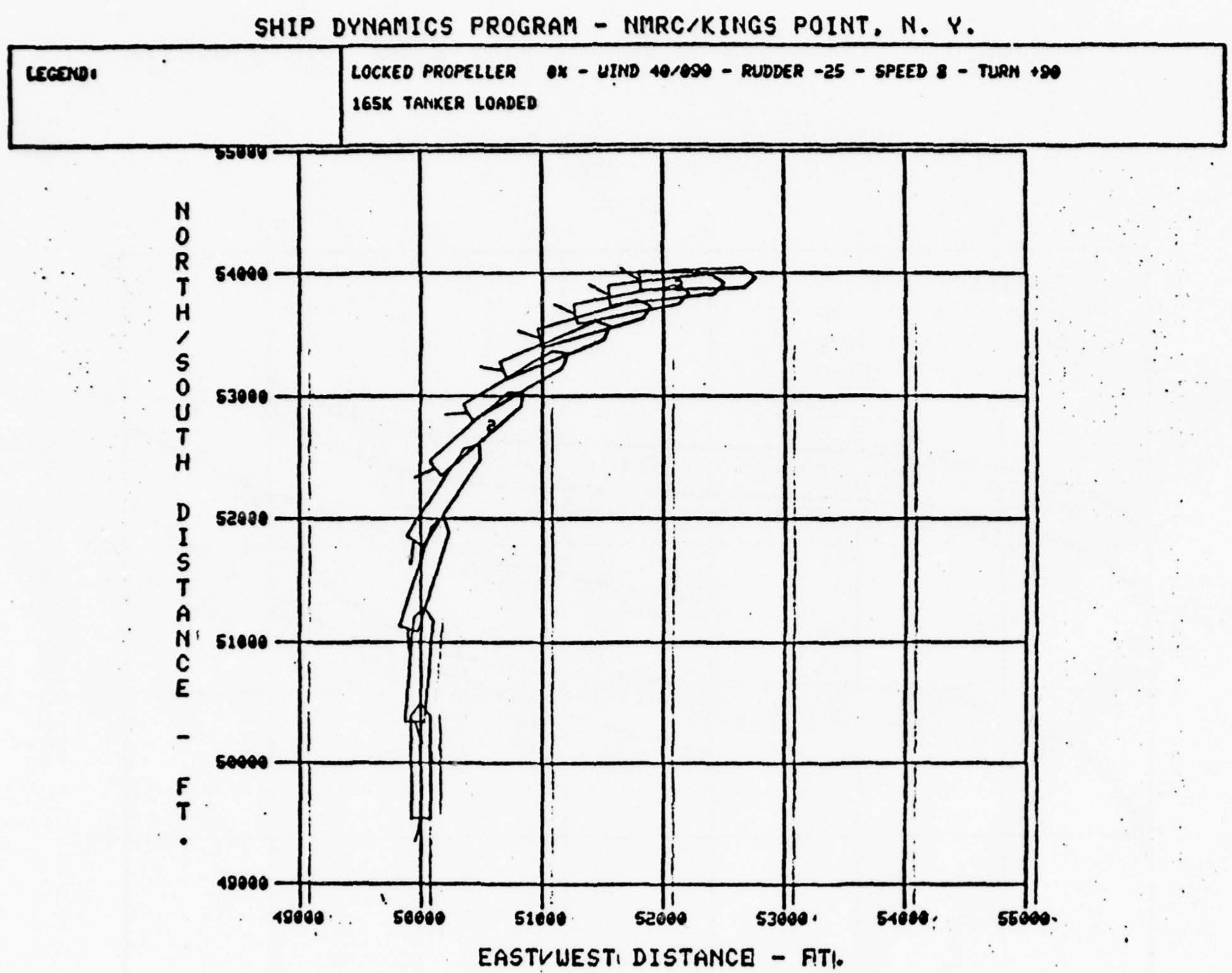

Figure 2-9. Propeller Drag Comparisons (Part 4)

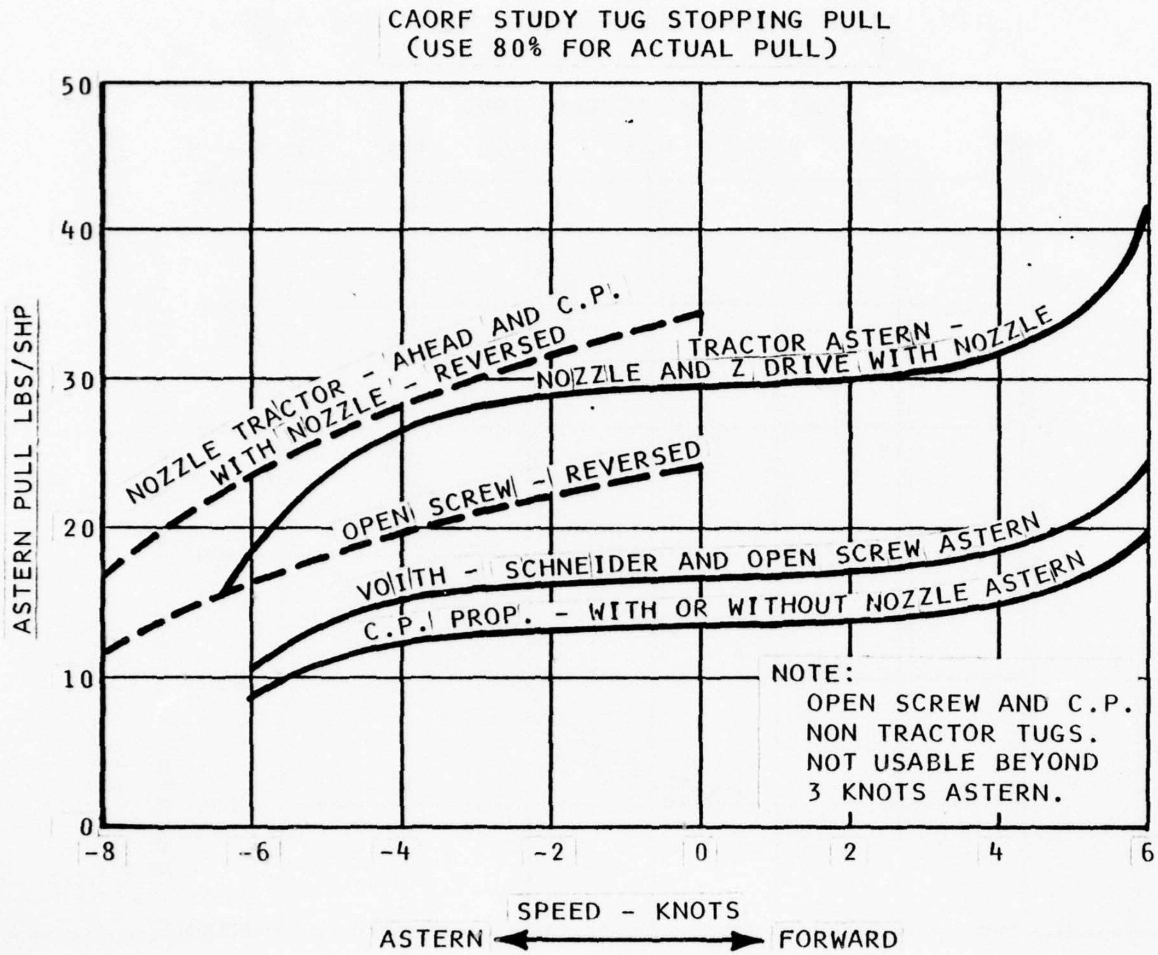

Figure 2-10. Tug Astern Forces at Different Ship Speeds

There were delays imposed from the time of the hypothetical failure until the tugs were allowed to pull. The first delay was a time delay of 90 seconds. It was conservatively estimated that 30 seconds would pass before the bridge crew would be alerted to the failure and request tug assistance. It was further estimated that 60 seconds would be required for the tugs, on soft lines, to drop back into position and tighten up on the lines by backing. The total delay was 90 seconds.

A further delay, related to speed, was imposed. In certain runs, the ship speed through the water was initially as high as 10 knots. Tug forces were not allowed to be implemented until the ship's fore/aft speed through the water was reduced to 6 knots (see Figure 2-10). In those cases where ship speed was already at or below 6 knots, only the 90-second delay pertained.

2.5.5.2 Tug Forces on the Simulator

The use of tugs on the simulator during the man-in-the-loop experimentation differed in some respects from the off-line implementation. There was only one ship size to consider, the 165K DWT tanker, and ship speeds were never more than 6 knots through the water. As a result, no delay caused by the ship moving faster than 6 knots had to be imposed.

The bridge crew was given 15 seconds from the time of the failure to become alerted to the failure. If by the end of 15 seconds they were not alerted, a simulated call from engine room to the bridge was made by the chief engineer to so advise them. Once the tugs had been requested, a 60 second delay was imposed as in the off-line runs.

In addition, the pulling power for the pair of tugs available on the simulator was continuously varied according to ship speed in agreement with the forces in Figure 2-10

with u signifying fore/aft speed of the ship through the water. The maximum tug force (per tug) was varied according to:

5.5 kts $\leq u \leq 6.0$ kts: Tug Force = 109,000 lbs.
4.0 kts $\leq u < 5.5$ kts: Tug Force = 97,000 lbs.
0 kts $\leq u < 4.0$ kts: Tug Force = 80,000 lbs.

2.5.6 Wind Force and Moment Equations

The aerodynamic (wind) forces depend on the exposed area of the ship above the waterline, the distribution of that area, and the relative speed and direction of the wind. Therefore, the forces, and particularly the moments, are strongly influenced by vessel loading, trim, and the location of the superstructure. The vessels in this study were fully loaded, even-keeled and with the house aft.

The wind forces and the moments can be simply, but satisfactorily approximated by the following expressions

$$\text{(surge)}\quad X_{wind} = \tfrac{1}{2}\rho_a L^2 V_{wr}{}^2 \cos \Psi_{ar} (C_x)$$
$$\text{(sway)}\quad Y_{wind} = \tfrac{1}{2}\rho_a L^2 V_{wr}{}^2 \sin \Psi_{ar} (C_y)$$
$$\text{(yaw)}\quad N_{wind} = \tfrac{1}{2}\rho_a L^3 V_{wr}{}^2 (C_{n1} \sin \Psi_{ar} + C_{n2} \sin 2\Psi_{ar})$$

where ρ_a is air density, V_{wr} is relative wind speed, Ψ_{ar} is relative angle between direction from which wind is blowing and ship heading, L is the ship length.

The coefficients C_x, C_y and C_{n1} are all negative. The coefficient C_{n1} essentially accounts for the moment due to the ship hull area exposed to the wind, and C_{n2} accounts for the superstructure and the trim. The relative magnitudes of C_{n1} and C_{n2} determine whether the ship falls off from or luffs into the wind. For loaded tankers with aft houses the tendency is to luff into the wind.

The variation of wind forces and moments is illustrated in Figure 2-11 for the 80K tanker making 4 knots and exposed to a relative wind of 40 knots. The wind directions are those of the apparent wind relative to the longitudinal axis of the vessel. The surge force changes from a retarding force to a pushing force when the relative wind direction swings past a beam wind, the sway force symmetrical with respect to a beam wind, and the yawing moment has a broad peak centered around a wind direction approximately 30^{o} abaft the beam.

The wind forces significantly affect the rudder angle, the sideslip angle and the engine RPM required to maintain a constant speed and course. Table 2-8 presents the equilibrium conditions for an 80K and a 280K tanker at several different ship speeds for a 40-knot wind coming from a bearing of 45^{o}, 90^{o} and 135^{o}. These data are plotted in Figures 2-12 and 2-13.

It can be seen that the maximum rudder angle occurs at the lowest ship speed (4 knots) for a relative wind direction further abaft the beam than might be expected. The maximum sideslip angle, on the other hand, occurs at low speed, when the wind is somewhat forward of the beam. As the speed of the vessel increases, the rudder angle required for equilibrium decreases and the peak rudder angle shifts closer to the abeam position. The amount of rudder required to trim the vessel for 40-knot winds abeam or aft of the beam is significant at the 4- and 6-knot speeds and is relatively small at the higher ship speeds.

The rudder required to trim the vessel depends primarily on the ratio of wind speed to ship speed for any given wind direction. When this ratio reaches a value of about 10, the maximum trim rudder angles approach or exceed the available

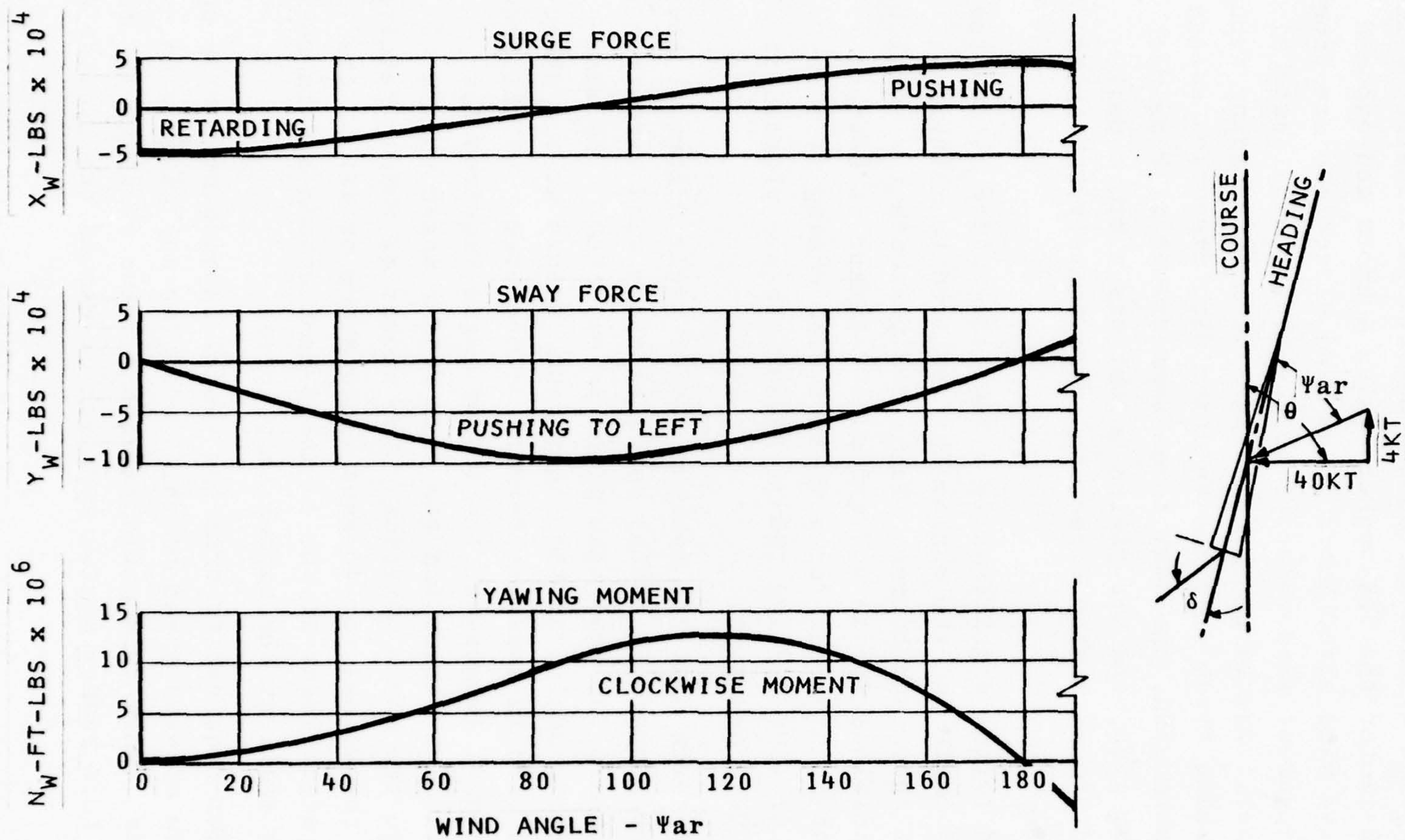

Figure 2-11. Wind Forces and Moments, 80K DWT, 40 kt. Wind.

TABLE 2-8. EQUILIBRIUM CONDITIONS

Wind = 40 kt.

Tanker	Ship Speed	Wind Direction	Heading (deg.)	Rudder (deg.)	Sideslip (deg.)	RPM
80K	4 kt.	45	4.17	8.33	4.1	38.3
	"	90	5.35	18.45	5.3	31.0
	"	135	3.48	29.29	3.6	17.7
	6 kt.	45	1.98	5.68	2.0	46.7
	"	90	2.24	12.47	2.3	39.5
	"	135	1.00	13.79	1.1	29.7
	8 kt.	45	1.16	4.11	1.2	56.5
	"	90	1.25	8.21	1.3	49.8
	"	135	.54	7.62	.6	42.7
	10 kt.	45	.78	3.10	.8	67.0
	"	90	.81	5.61	.8	60.9
	"	135	.34	4.70	.3	55.4
280K	4 kt.	45	4.28	6.40	4.1	36.3
	"	90	4.97	16.40	4.9	28.0
	"	135	-no equilibrium condition existed-			
	6 kt.	45	2.01	4.09	2.0	44.7
	"	90	2.25	9.49	2.3	36.7
	"	135	1.06	13.24	1.1	26.5
	8 kt.	45	1.19	2.84	1.2	54.1
	"	90	1.29	5.87	1.3	47.0
	"	135	.58	6.55	.6	39.7
	10 kt.	45	.80	2.10	.8	64.2
	"	90	.85	3.92	.9	57.8
	"	135	.37	3.58	.4	52.1

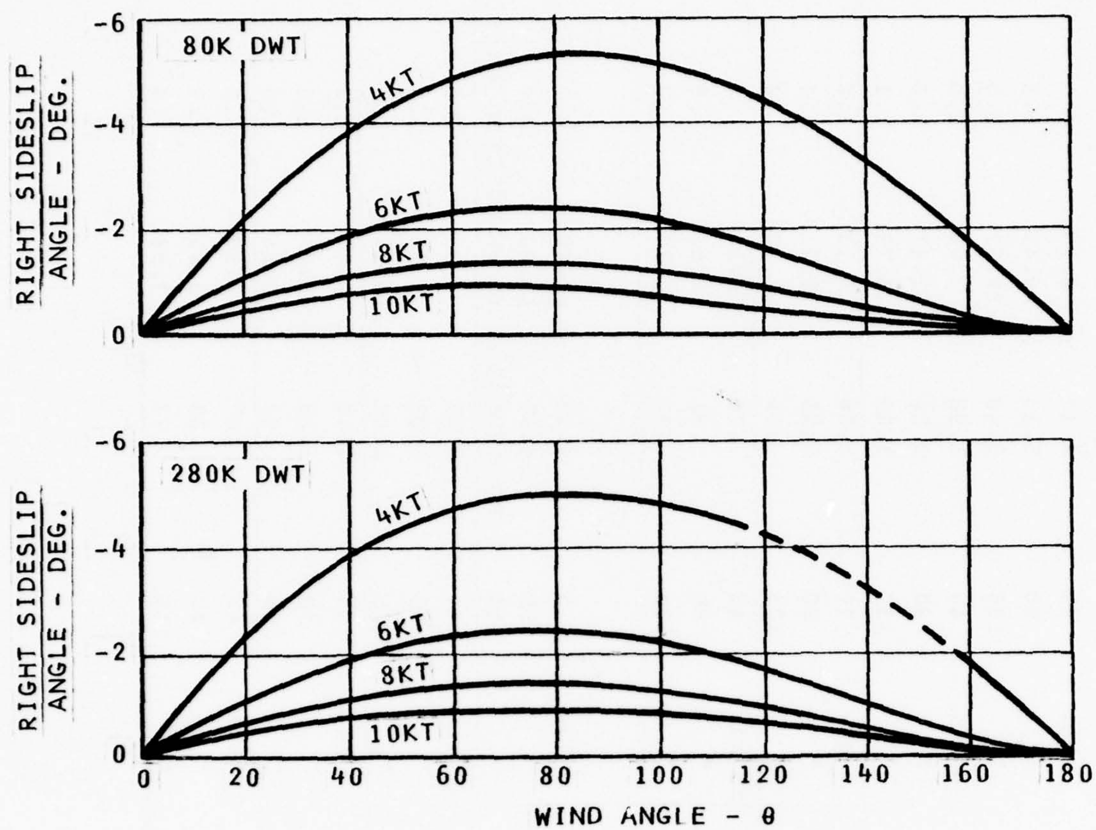

Figure 2-12. Equilibrium Sideslip Angles, 40 kt. Wind.

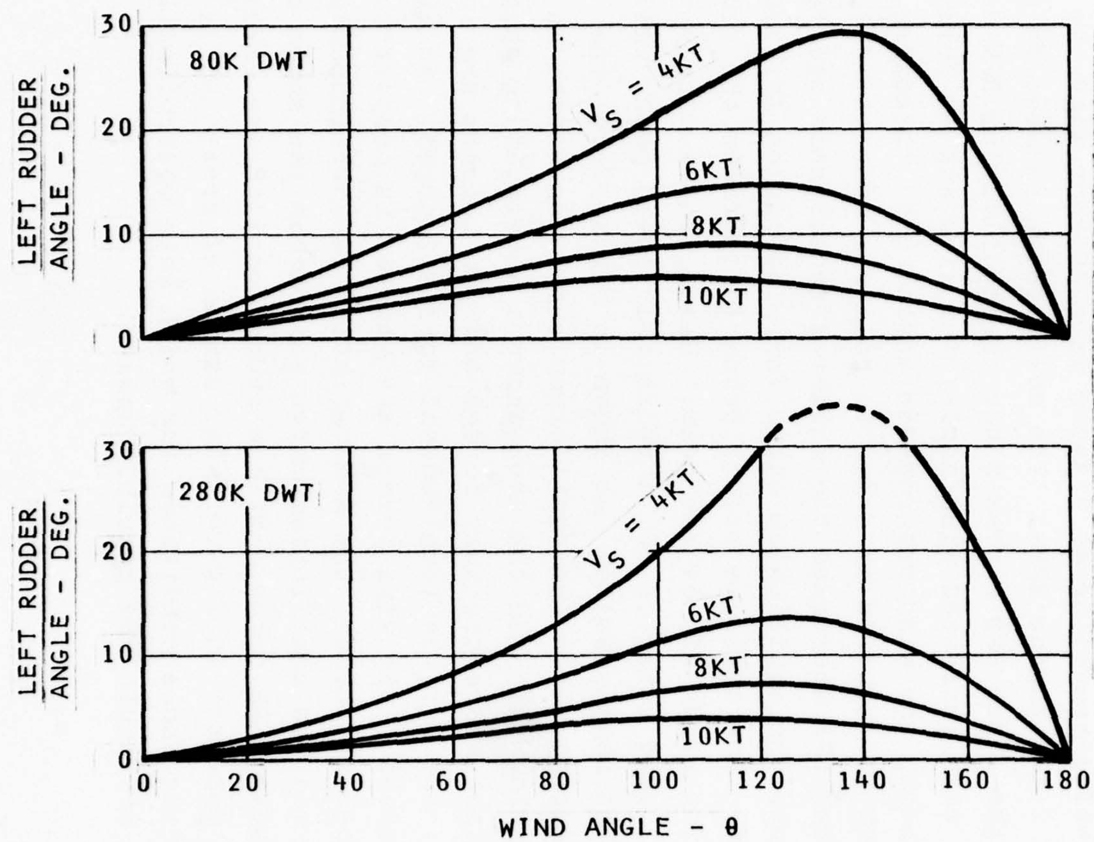

Figure 2-13. Equilibrium Rudder Angles, 40 kt. Wind

rudder (35^{o}), which leaves the vessel with little or no maneuvering capability in one direction. As is well known, the effectiveness of the rudder is increased as engine RPM is increased. This influences the shape of the equilibrium rudder angle curve as shown in Figure 2-13. The dashed curves represent the rudder angle required to trim the vessel while traveling at 4 knots in a 40-knot wind, at several fixed engine RPMs. The solid curve is seen to cut across the fixed RPM curves since the equilibrium RPM decreases with increased wind angle; for wind angles forward of the beam, the wind retards the vessel and, therefore, added RPM is required in order to hold the speed of 4 knots. This added RPM increases the rudder effectiveness and tends to depress the equilibrium curve for wind angles forward of the beam. The opposite effect tends to increase the rudder angles for winds aft of the beam. Hence, for a wind speed to ship speed ratio of 10, a relatively steep peak, well aft of the beam results. As shown in Figure 2-14, the shaded region below the equilibrium curve represents an accelerating ship and the area above a decelerating ship at the instant where the sway forces and yaw moments are in balance, but not the longitudinal forces (surge). At higher vessel speeds, the wind forces are smaller in proportion to the propeller thrust, the RPM variation is correspondingly reduced and the equilibrium curve approaches the shape of the constant RPM curve. Static rudder equilibrium curves, such as depicted in Figure 2-14, can be of great use in determining those conditions for which ship controllability becomes difficult and possibly unsafe.

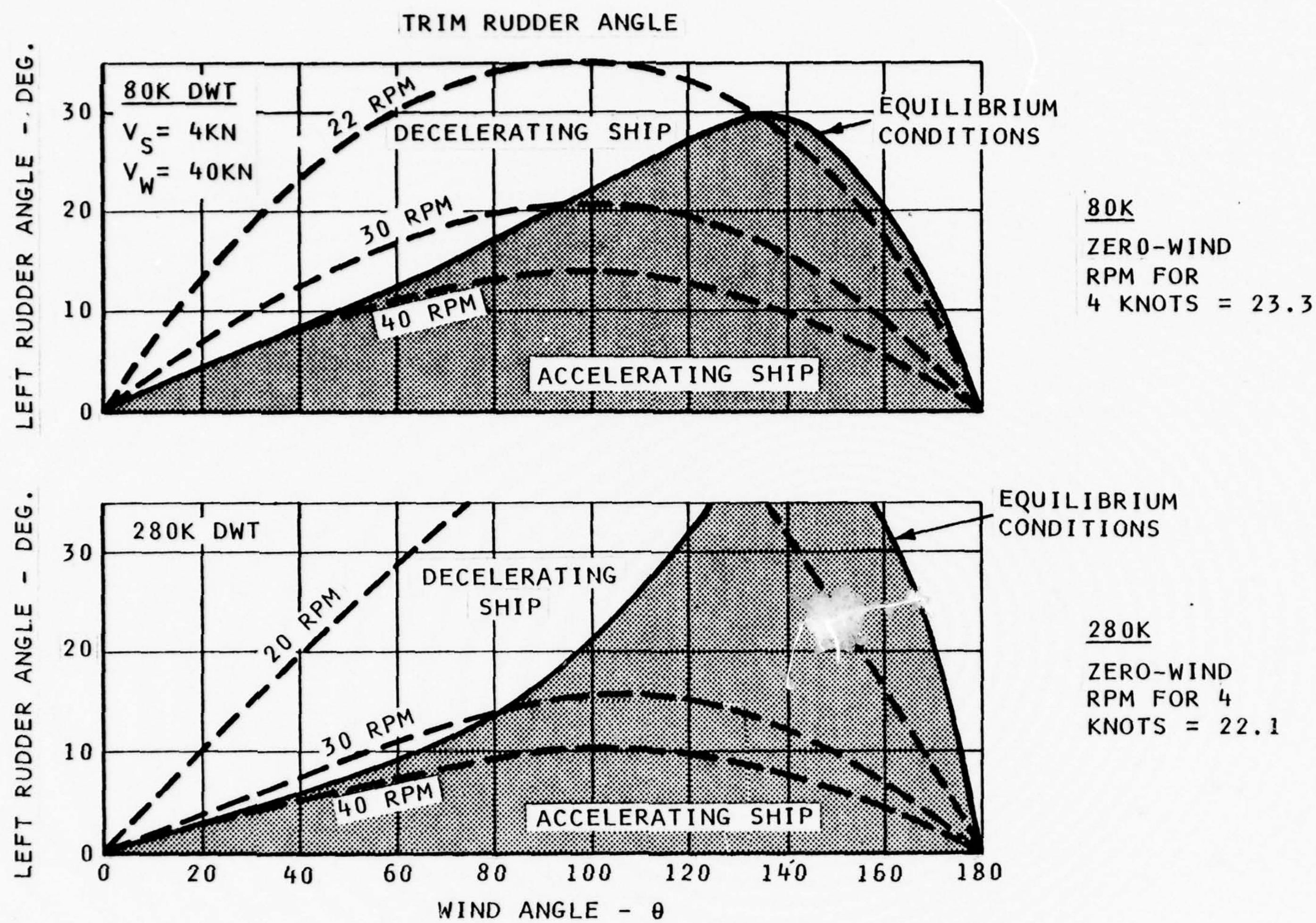

Figure 2-14. Effect of Engine RPM on Trim Rudder Angles

SECTION 3

OFF-LINE TRACK-KEEPING STUDY

3.1 INTRODUCTION

The purpose of the off-line track-keeping study was to investigate the capability of the ships to maintain the designated tracks under extreme but realistic tidal current and wind conditions. Simulated passages were conducted for a range of ship sizes and ship speeds through the critical portions of the various routes of interest.

3.2 METHODOLOGY

3.2.1 Track Definition

Each of the routes of interest was examined and certain portions were selected for the simulated track-keeping runs. The criteria for selection were proximity of shoals, rocks, or land and the need for significant changes in direction. It was deemed unnecessary to perform simulated transits of the straight portions of the various routes since the vessel would soon determine the required rudder, sideslip angle and RPM for equilibrium and would run along the track indefinitely with little or no deviation.

The track lines to be followed were selected by a Puget Sound pilot to insure that they were consistent with the local conditions. These tracks were programmed into the simulation and it was the goal of the vessel to follow them as closely as possible.

3.2.2 Selection of Environmental Conditions

The critical portions of the various routes studied all have a strong north-south component. To provide a severe test of the track-keeping capability of the vessels, beam winds from the west (270°) and the east (90°) were chosen. These

winds, generally, exert the largest side force on the vessel and, it was felt, would tend to create the maximum conditions for blowing the vessel off track. As indicated in paragraph 2.5.6, the maximum side force (beam wind) does not necessarily result in the greatest maneuvering degradation, i.e., the maximum rudder required to hold the ship on a straight course occurs at a relative wind condition well abaft the beam (quartering wind). However, because these runs analyzed the critical portion of the track-keeping task (during and immediately following a turn), the beam wind was selected so that it would present difficulty before and after the turn. Furthermore, at the critical low ship speed conditions, the vessels needed rather large crab angles to remain on track. The net result is that the most critical wind direction cannot easily be determined and, with the east-west wind combination, the vessel is often exposed to the maximum trim rudder conditions during turns and on some straight runs.

The tidal currents along each route were determined from the applicable NOAA tidal current tables. The maximum ebb and flood tide currents were imposed in appropriate sections along the track. It should be noted that rather large cross currents existed on some of the legs since the currents are not constrained to follow the channels.

3.2.3 Track-Keeping Autopilot

The control of the vessel during the track-keeping runs is provided by an automatic controller (autopilot). This autopilot generates a desired rudder angle, δ_d, essentially using the following relation: $\delta_d = a(\Psi - \Psi_d) + b\dot{\Psi} + c\ell p$

where

$\Psi, \dot{\Psi}$ = yaw and yaw rate of the ship

Ψ_d = desired course heading = channel course

ℓ_p = deviation distance from the ship to the course line

a,b,c = constants for a particular vessel.

The first term, $a(\Psi - \Psi_d)$, of the autopilot drives the ship on to the proper heading. The second term $(b\dot{\Psi})$ is a damping term which prevents the vessel from excessive overshooting of the desired heading. The last term $(c\ell p)$ drives the ship on to the designated ground track. An autopilot schematic is shown in Appendix D.

The autopilot must be "switched" to the next track at a time that is a function of a particular ship and its handling qualities and the speed at which it is approaching the turn. A systematic procedure was used to determine a reasonable turn point, taking tidal current into account. The behavior of the autopilot in handling channels with turns is illustrated in Appendix D.

During some track-keeping runs, the vessel was unable to maintain the target speed with the engine RPM held constant. This would be particularly apparent during and immediately following a turn. An engine speed control algorithm was programmed into the simulation so that vessel speed was held to the target value plus or minus 10 per cent.

3.2.4 Initial Conditions

To insure that the vessel started the run in an equilibrium state on track, under the existing environmental conditions, the run was started several miles prior to the desired start point. During this initial period, the autopilot achieved the equilibrium rudder, sideslip and RPM needed to maintain the vessel on track.

3.2.5 Performance Measures

To provide a rational basis for evaluating the track-keeping capability of the vessels under the various run conditions, some measure(s) of performance are required. The level of track-keeping performance during a simulated passage can be determined by subjectively examining the ground track plot and by recording maximum off-track deviations. A typical ground track plot is presented in Figure 3-1.

The crucial portion of the ground track is during and immediately following a turn. In Figure 3-1 it can be seen that the ship followed the track closely at all times. This would be subjectively rated as excellent performance. As the track deviations become larger due to reduced ship speeds under the influence of the prevailing currents and wind, the performance is rated correspondingly poorer.

There are several parameters associated with the track-keeping task that were measured since they contribute to track-keeping performance and would help explain the trends or highlight extreme conditions. Rudder angle measurements fall into this category. Two types of rudder angle measurements were made:

1. Equilibrium rudder prior to a turn - This is an indication of the amount of rudder available to start the vessel swinging into the turn. Large amounts of trim rudder are unsatisfactory, even in the straight portion of the track since little margin is provided for safe maneuvering in one direction.
2. Time spent at high rudder angles - This is an overall measure of rudder availability. Large rudder angles held for a short time during a run are not as bad as large rudder angles required almost continuously. The

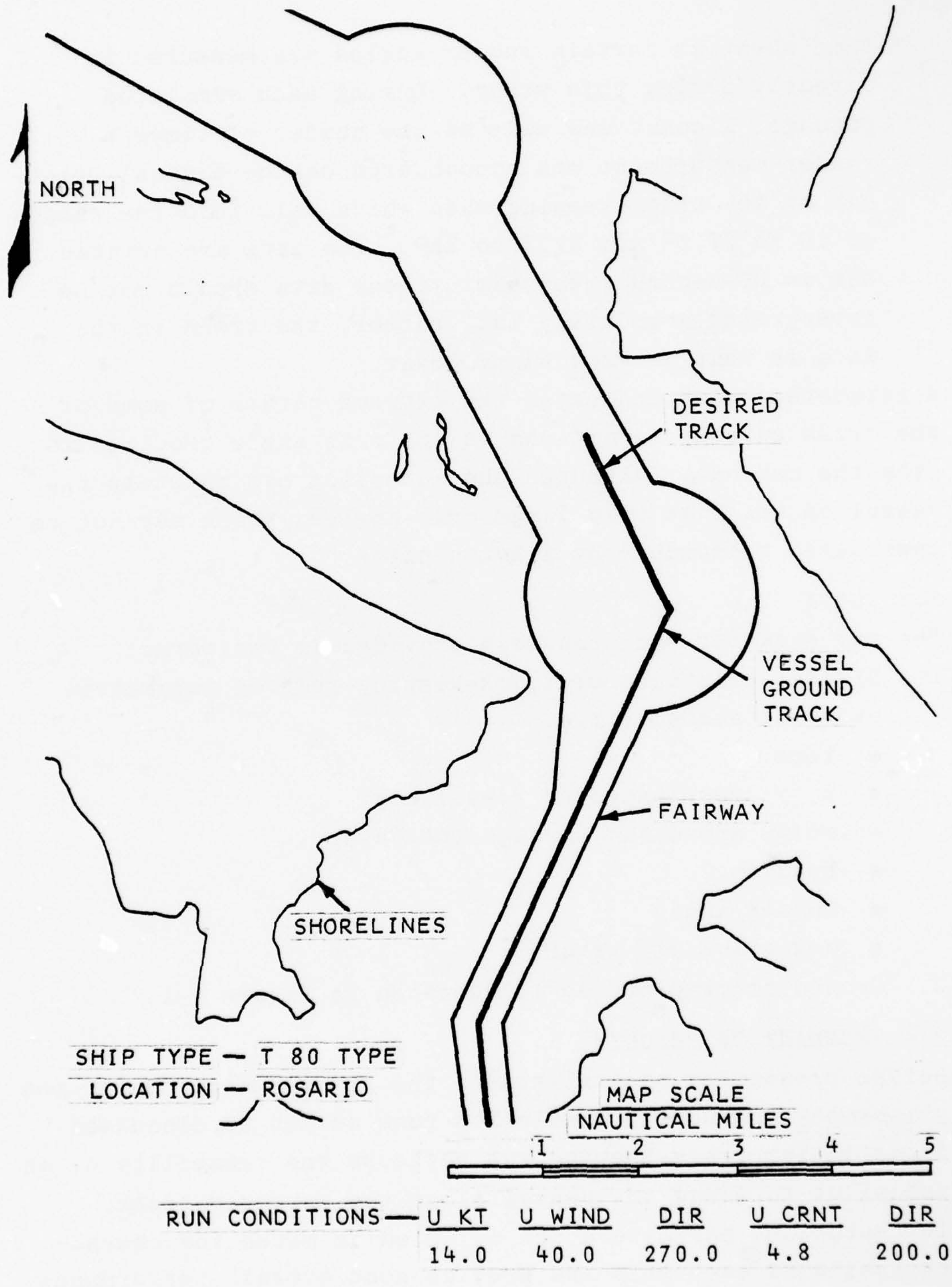

Figure 3-1. Typical Ground Track Plot

time spent at certain rudder angles was measured indirectly during this study. During each simulated passage, a count was made of the number of times a rudder measurement was encountered on the digital printout of the track-keeping data which fell into the ranges of 20 to 27.5° and 27.5 to 35°. The data are printed out in 30-second intervals. These data should not be interpreted absolutely but, rather, the trend in the data is what is most significant.

A parameter which indicates the extreme nature of some of the cross current conditions is the crab angle required to stem the current. Although the autopilot can maintain the vessel on track at very large crab angles, these may not be considered reasonable by a human pilot.

3.3 DATA

The raw data for each run were provided in two forms:

1. Digital printouts of track-keeping related parameters every 30 seconds; i.e.
   - time
   - x, y coordinates of vessel c.g.
   - ships speed (u) through the water
   - heading
   - rudder angle
   - deviation off-track
2. Ground track plots as illustrated in Figure 3-1.

3.4 SUMMARY OF RESULTS

Before presenting an analysis of the track-keeping data, the philosophy behind the simulation runs should be discussed. A particular track-keeping run reflects the capability of an autopilot to steer the vessel along the intended track. The autopilot parameters are adjusted to match the characteristics of each ship and provide good overall performance.

Although the ship speed and the environmental conditions change during each run, the autopilot parameters are held constant. Any changes in track-keeping performance, therefore, represent the ability of a preprogrammed autopilot to cope with the changing conditions. It is the trend in performance that is significant. This point is emphasized to preclude the all-too-human tendency to inspect the data for a particular human pilot who might have anticipated the turn point better or who would have started the turn with an up-current bias, or who might have made more judicious use of the engine to hurry the turn, etc. Actually, based on inspection of the man-in-the-loop runs on the CAORF simulator, it appears that the autopilot often performs its track-keeping function more accurately than a human pilot.

3.4.1 Ground Track Analyses

A typical set of ground tracks is shown in Figure 3-2 for an 80,000 DWT tanker sailing through Rosario Strait, with a 40-knot east wind and maximum tidal current conditions. Note that the current for the 10-knot vessel speed through the water is head-on and for the lower ship speeds, it is a following current. These combinations were chosen in order to limit the ground speed to reasonable values. A comparison of the ground tracks shows that as ship speed decreases, the ship has progressively more difficulty negotiating the second turn, until at 4 knots, it goes outside the fairway during the turn. A subjective evaluation of these types of data for both east and west winds for three vessels which cover the deadweight tonnage range is presented in Figure 3-3. It is clear that vessel track-keeping performance (subjectively) improves with ship speed for both east and west winds. The vessels behave somewhat better on the average in a west wind and the 280K DWT tanker appears to behave somewhat poorer than the 80K or 400K vessels.

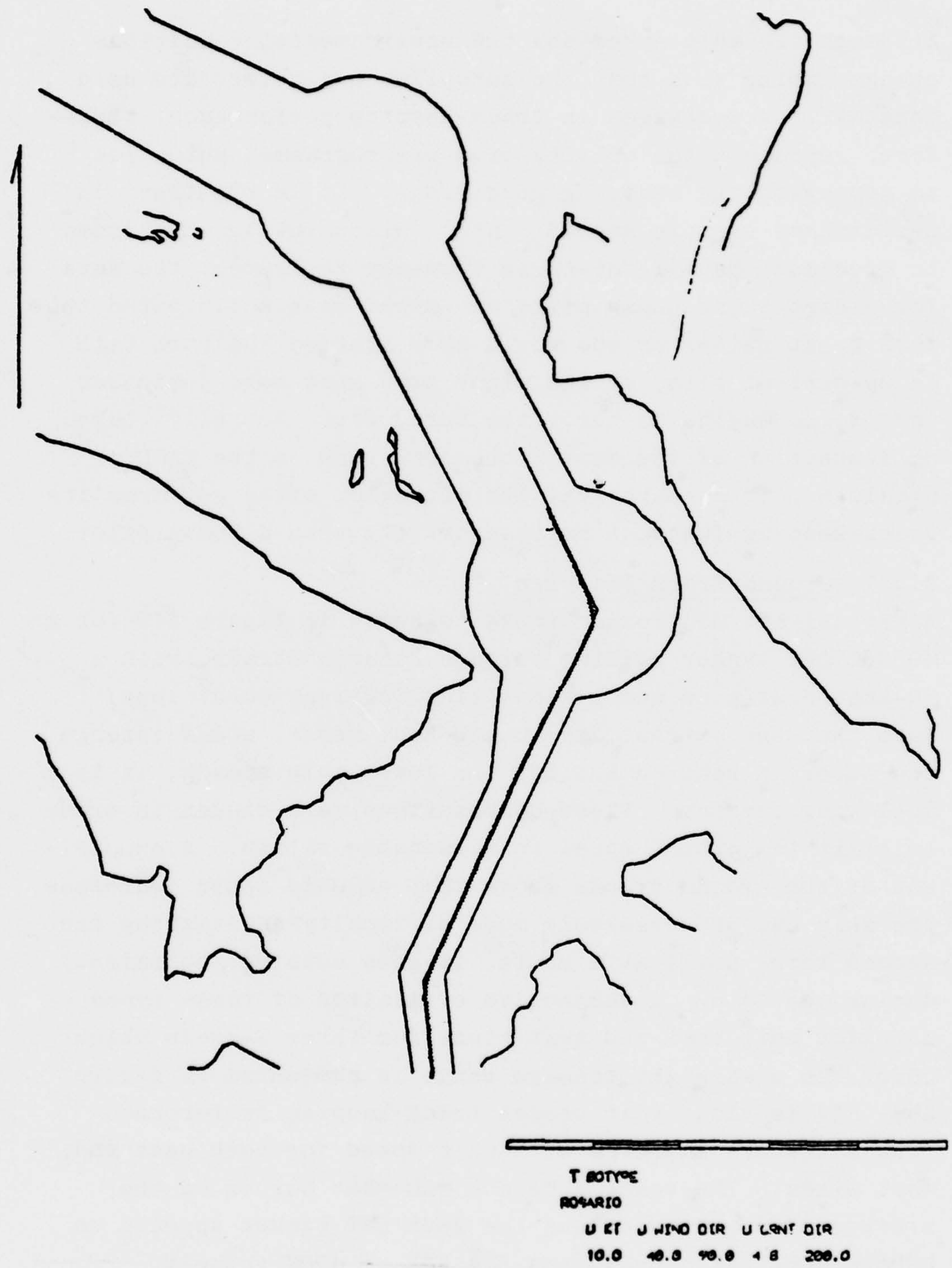

Figure 3-2. Ground Track, Rosario Strait (Part 1)

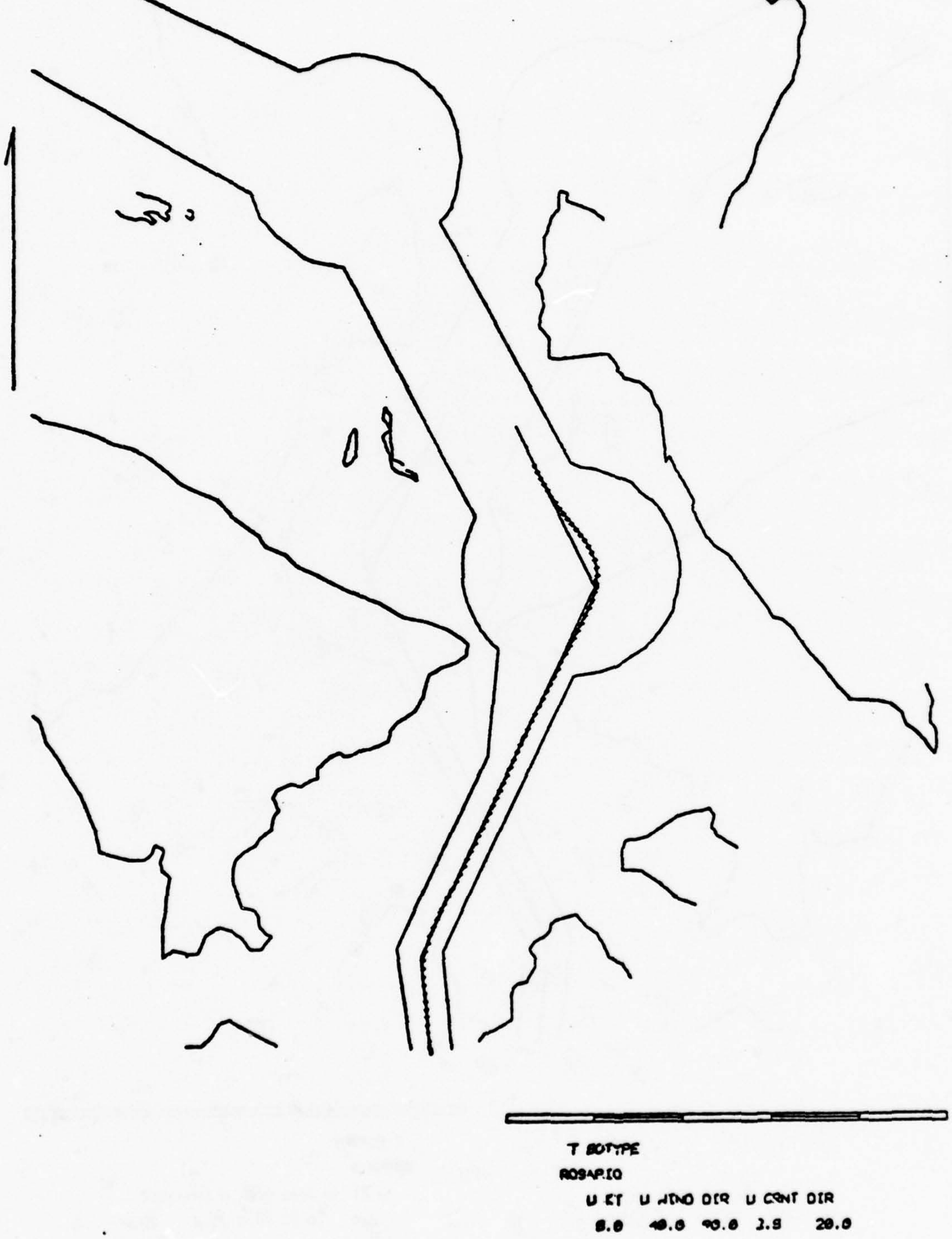

Figure 3-2. Ground Track, Rosario Strait (Part 2)

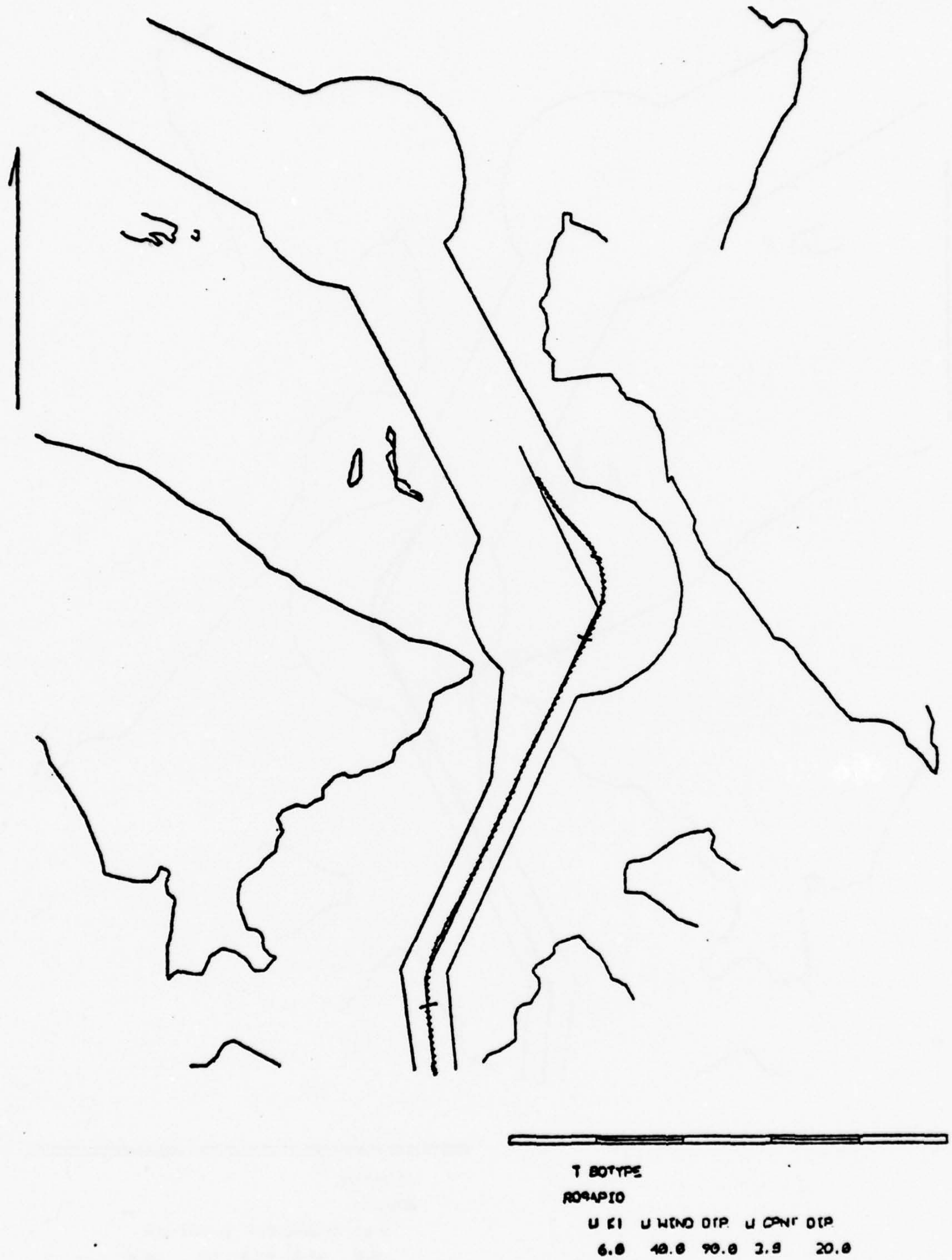

Figure 3-2. Ground Track, Rosario Strait (Part 3)

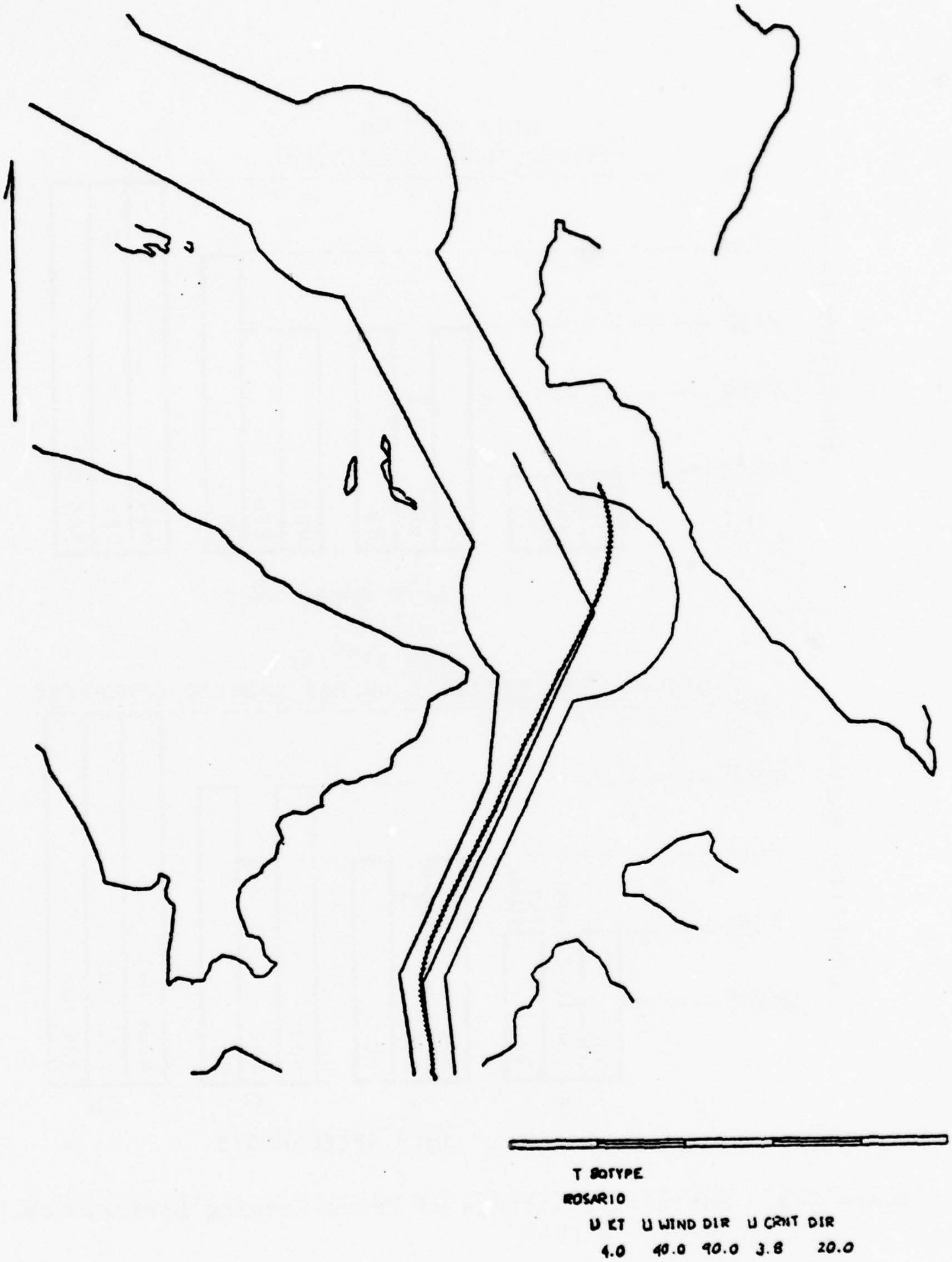

Figure 3-2. Ground Track, Rosario Strait (Part 4)

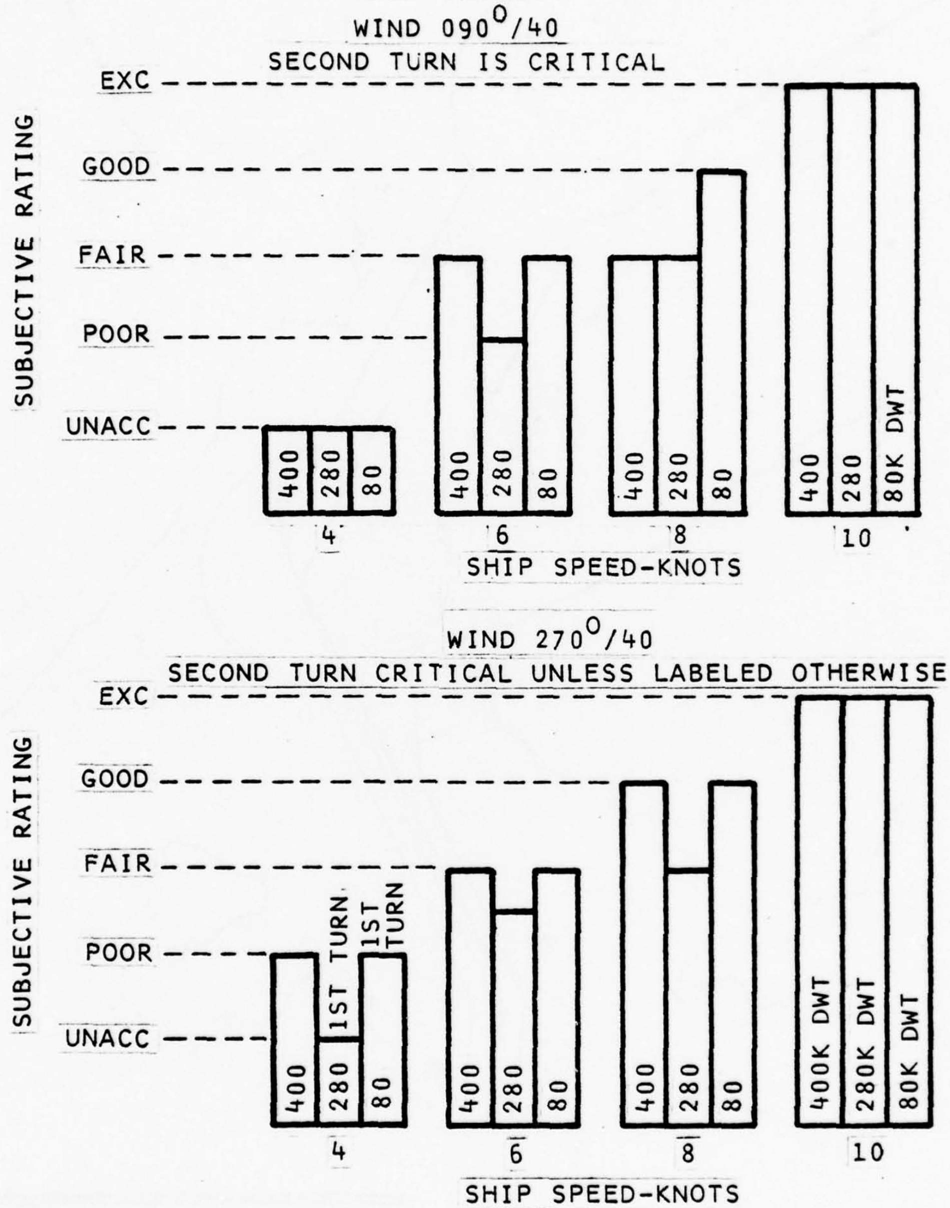

Figure 3-3. Subjective Ratings of Track-Keeping Performance, Rosario Strait

Generally, the critical problem with an east wind was the second turn, although at the lower speeds, the first turn also presented some problem.

Off-track deviation data were also gathered for the same ground tracks. These data are summarized in Figure 3-4. The same general conclusions that were reached subjectively apply to the quantitative results. However, the anomalous behavior of the 280K DWT tanker in east winds is more apparent in the plot. As will be shown later, the 280K DWT tanker has a disproportionately high trim rudder requirement i.e., the east wind fights the left turning moment generated by the rudder and reduces its ability to make a tight turn.

Another interesting aspect of the data in Figure 3-4 which is especially apparent in the east wind data, is that the off-track deviation is not directly related to vessel size. This is shown by the close correspondence in off-track deviation, between 6 and 10 knots, for the 80K and 400K DWT vessels.

Similar quantitative data are presented in Figure 3-4 for the 280K and 400K DWT tankers in Bellingham Channel (a typical ground track plot is shown in Figure 3-5). The third turn, which is a right turn, is generally the critical problem. For a right turn, a west wind is critical since it creates a left turning moment which opposes the rudder action. The 280K DWT tanker is again seen to have the larger off-track deviations.

An overview of all the ground track data suggest that a ship speed of 4 knots for the environmental conditions imposed, is too slow for an adequate vessel controllability. A 6-knot speed appears to be marginal, primarily for the 280K DWT tanker. An 8-knot speed through the water would appear to provide satisfactory controllability for all vessels.

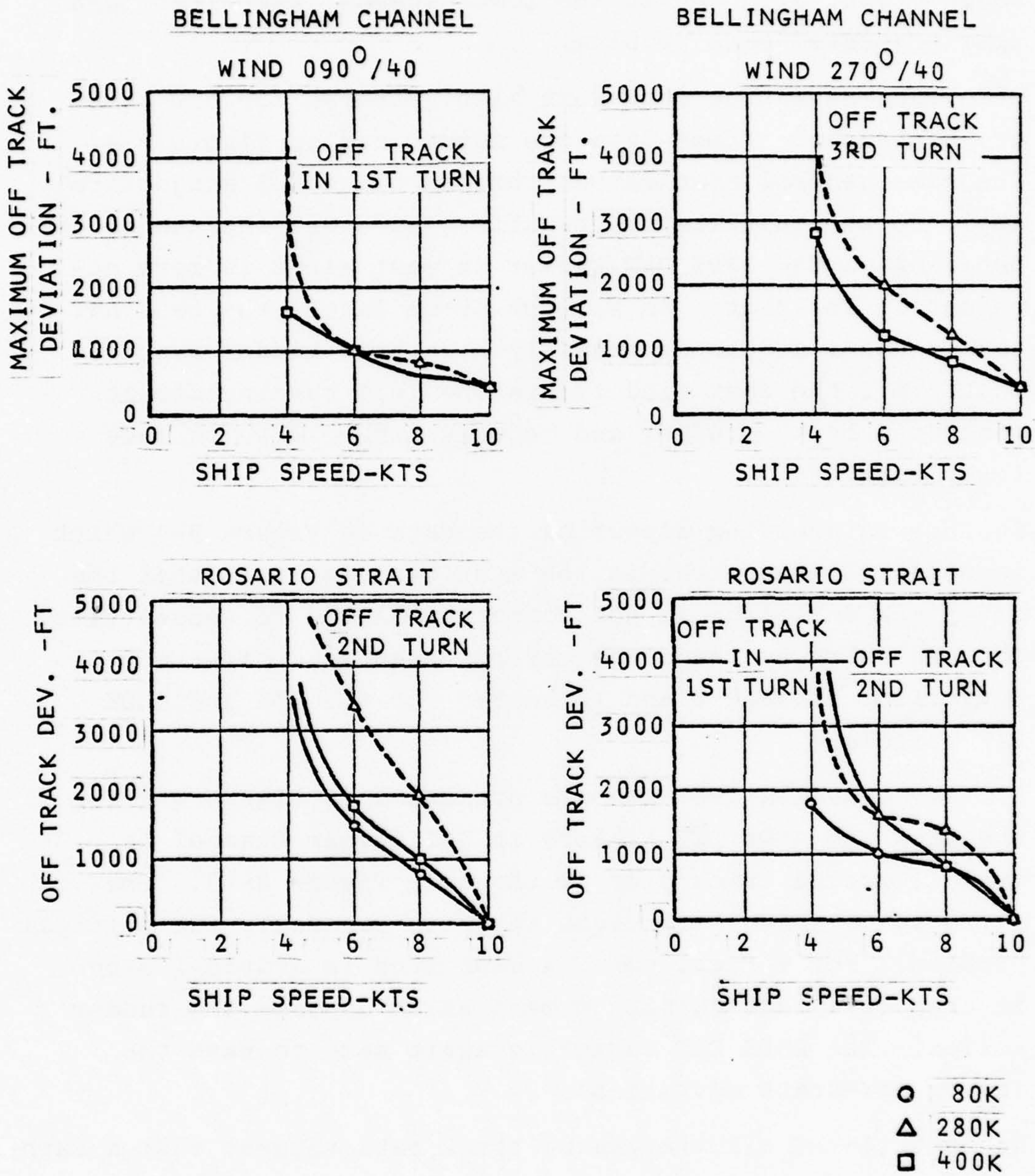

Figure 3-4. Off-Track Deviation

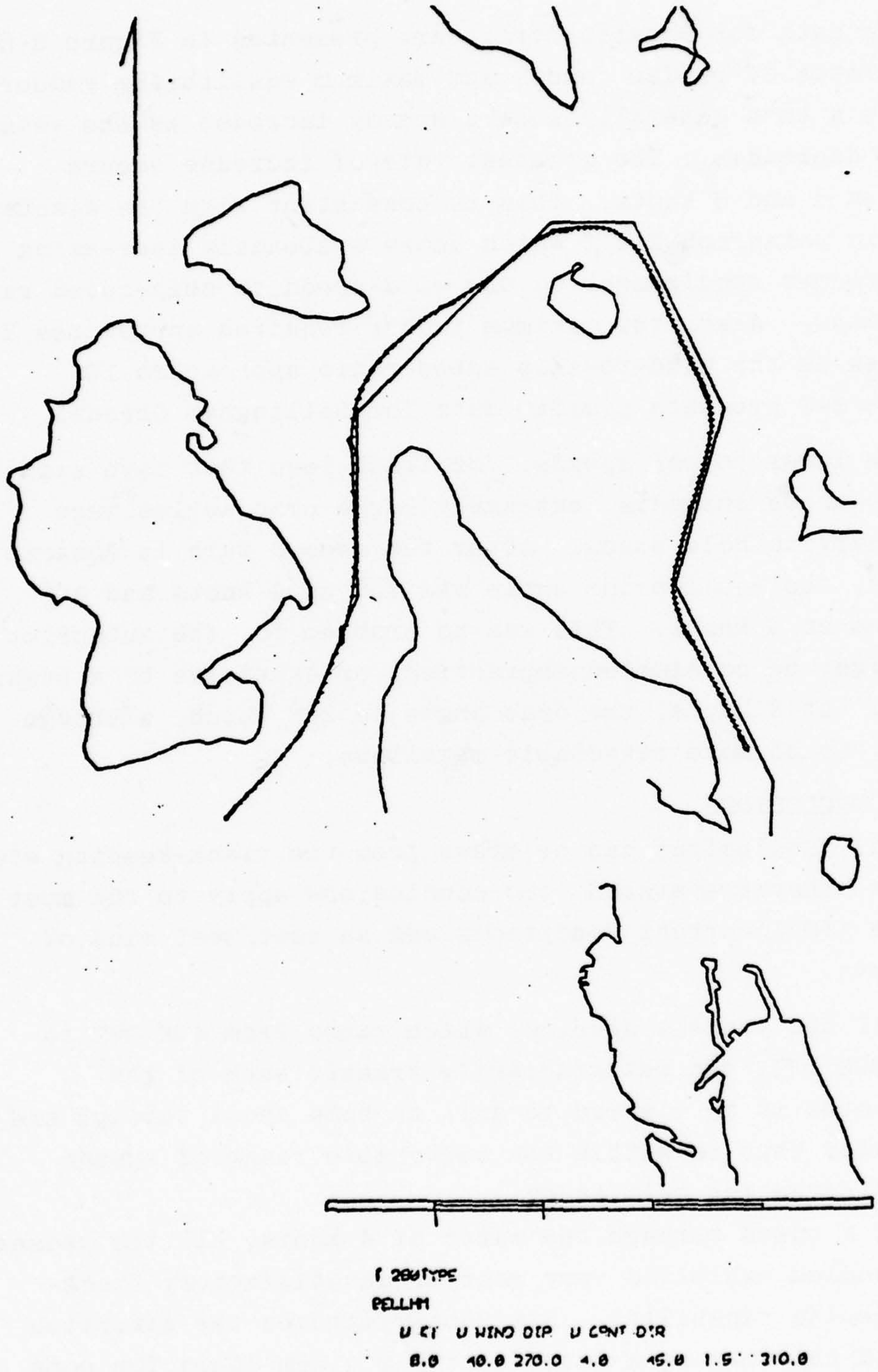

Figure 3-5. Ground Track, Bellingham Channel

Rudder data for Rosario Strait are presented in Figure 3-6. The trends of rudder counts and maximum equilibrium rudder before a turn generally show a steady increase as the vessel speed decreases. The greatest rate of increase occurs between 4 and 6 knots. This is consistent with the discussion in paragraph 2.4.5 which shows a steadily increasing turn rudder requirement as the wind-speed to ship-speed ratio increases. Also, the maximum rudder required approaches 35 degrees as the wind-to-ship speed ratio approaches 10. Figure 3-7 presents similar data for Bellingham Channel.

At the lower vessel speeds, for track legs that have significant cross currents, extremely large crab angles were necessary to hold track. After the second turn in Rosario Strait, the equilibrium angle was 45° at 4 knots and 30° degrees at 6 knots. This was no problem for the autopilot but might be considered impractical or excessive by a human pilot. At 8 knots, the crab angle is 20° which, although large, is of more reasonable magnitude.

3.5 CONCLUSIONS

Several conclusions can be drawn from the track-keeping study. Unless otherwise stated, the conclusions apply to the most severe tidal current conditions and an east/west wind of 40 knots.

1. All the vessels studied, which range from 40K DWT to 400K DWT, can satisfactorily transit each of the routes it is cleared to sail at some speed through the water that is within the reasonable range of speeds selected for this study.
2. At a speed through the water of 4 knots, all the vessels studied exhibited very poor or unsatisfactory track-keeping capability. Six knots improves the situation and this may be a satisfactory minimum speed for some

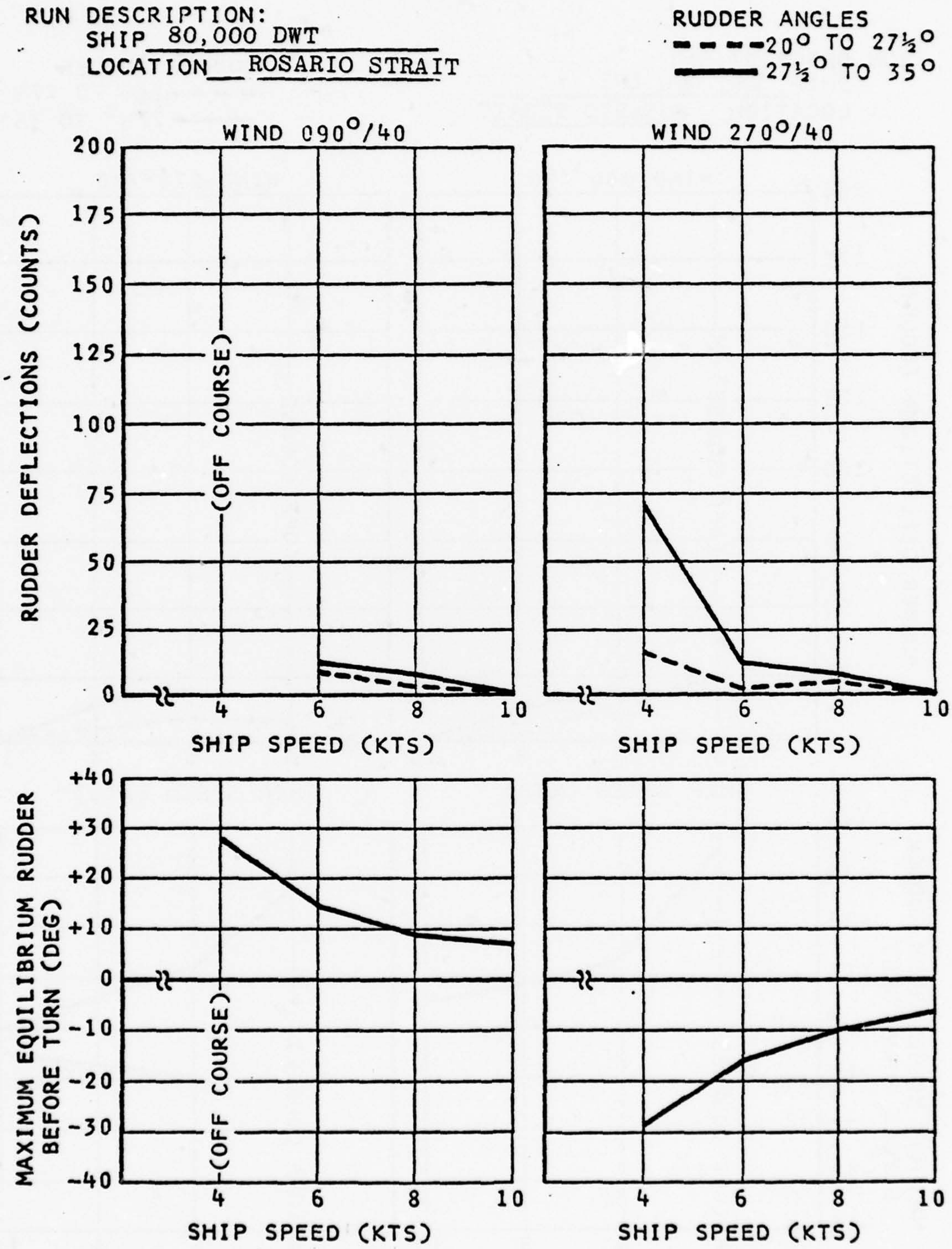

Figure 3-6. Rudder Data for Rosario Strait (Part 1)

RUN DESCRIPTION:
SHIP 280,000 DWT
LOCATION ROSARIO STRAIT

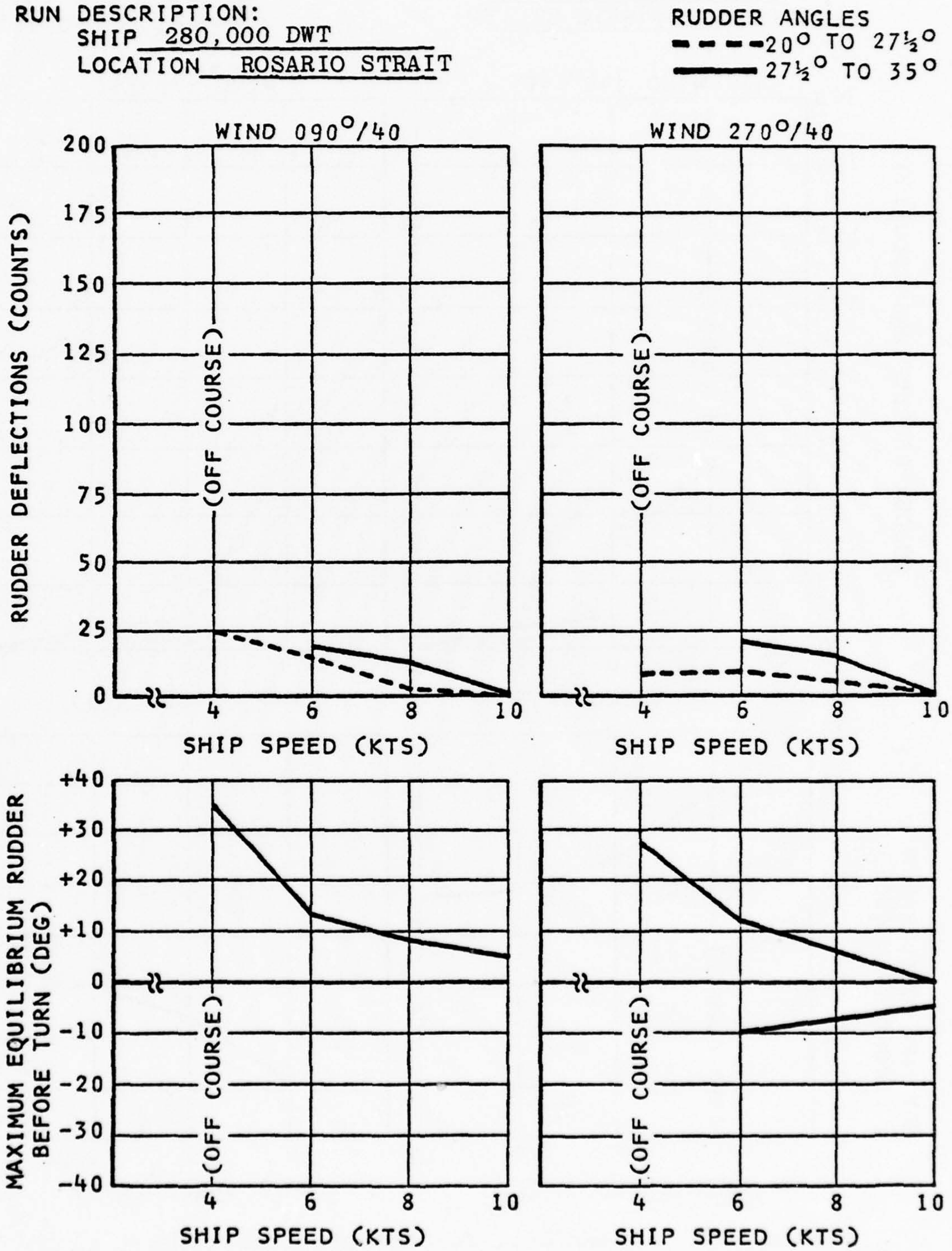

Figure 3-6. Rudder Data for Rosario Strait (Part 2)

RUN DESCRIPTION:
SHIP 400,000 DWT
LOCATION ROSARIO STRAIT

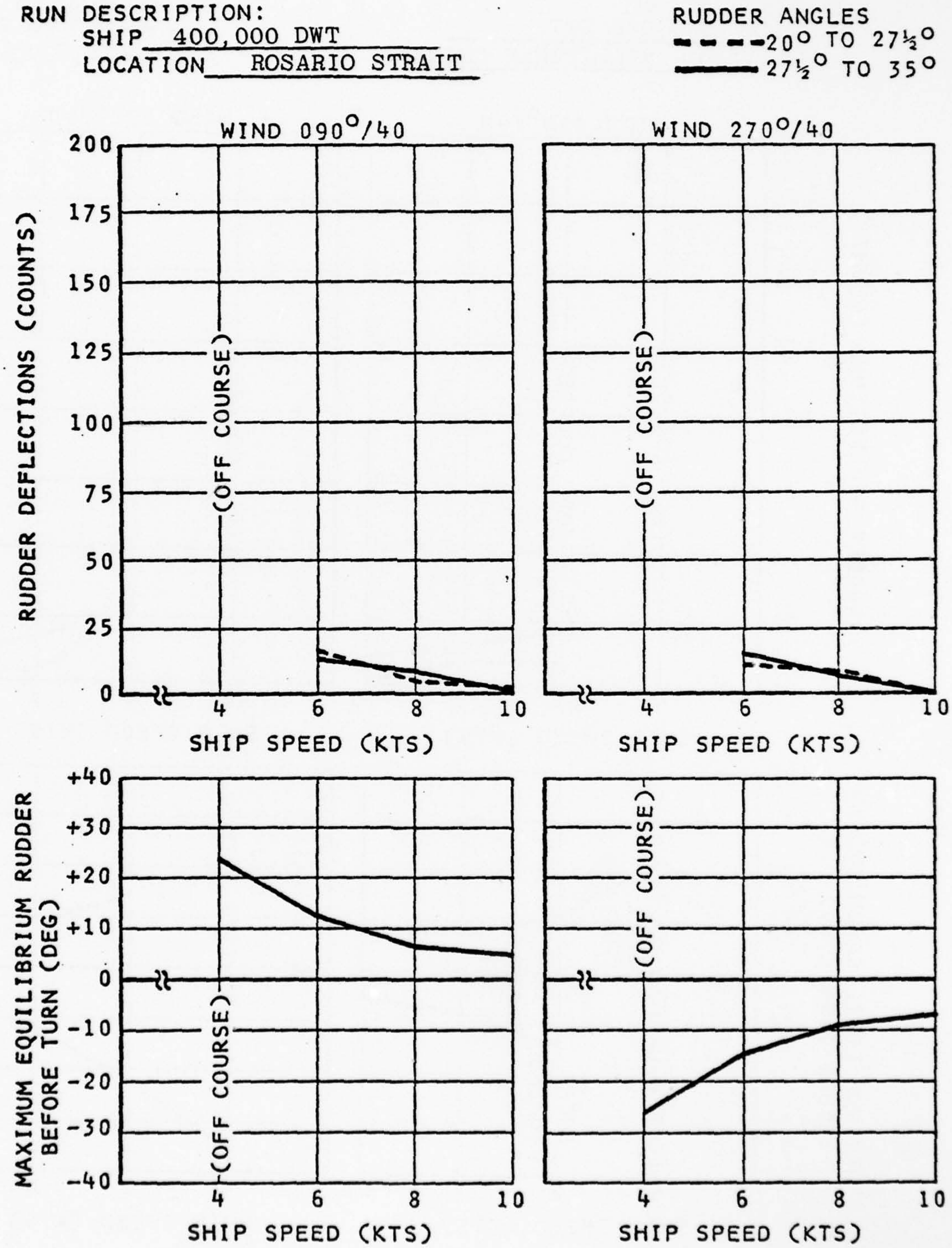

Figure 3-6. Rudder Data for Rosario Strait (Part 3)

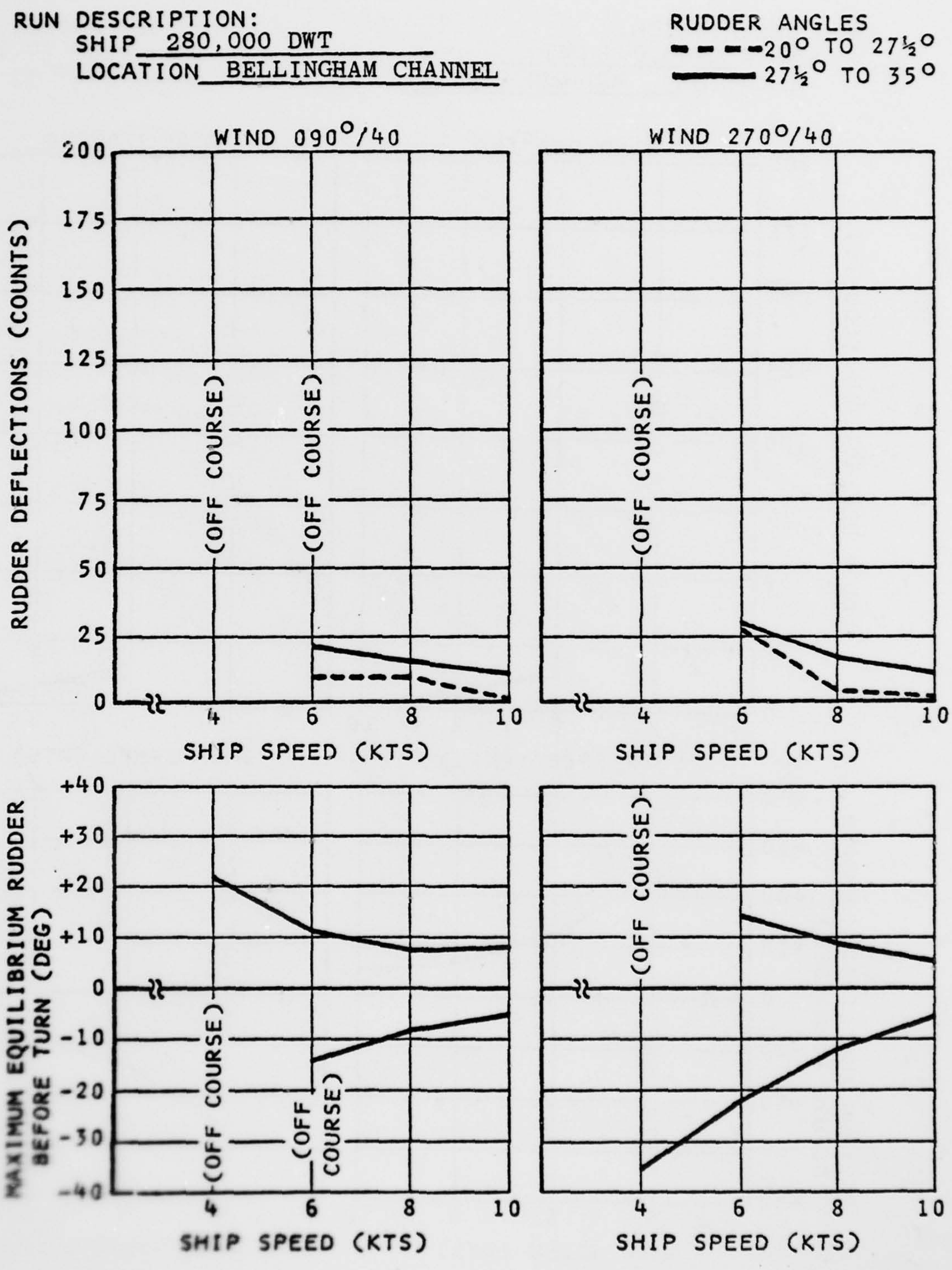

Figure 3-7. Rudder Data for Bellingham Channel (Part 1)

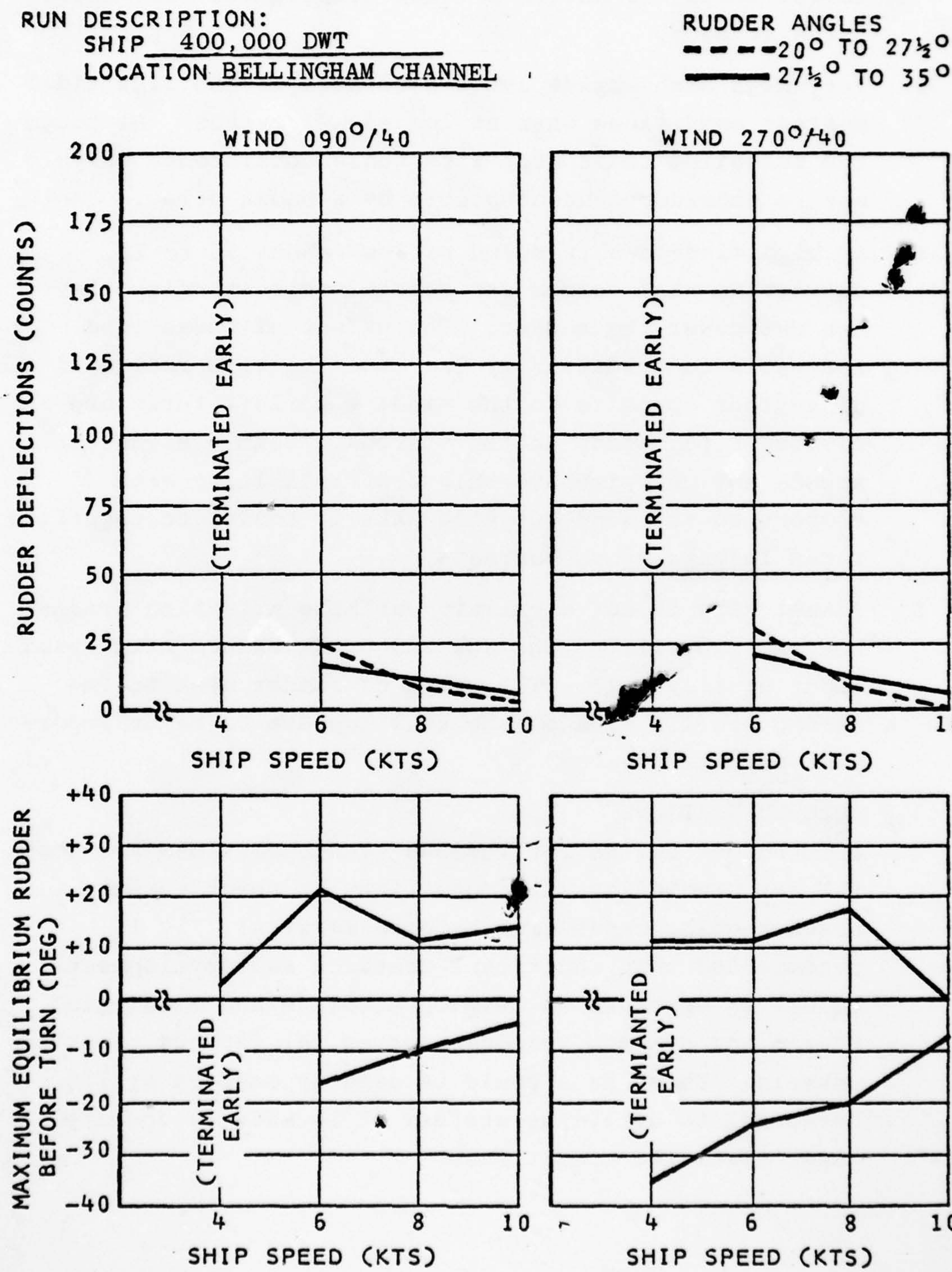

Figure 3-7. Rudder Data for Bellingham Channel (Part 2)

vessels. Eight knots appears to be a reasonable lowest speed for adequate track-keeping for all vessel sizes studied.

3. Very high crab angles are experienced at the high tidal current conditions when at low vessel speeds. Although the autopilot could cope with those conditions, they may be considered unacceptable by a human pilot.

4. At high wind-to-ship speed ratios (about 10 to 1), quartering wind forces can reach levels at which they can overpower the rudder. The effect of these wind forces is to dramatically increase the turn radius in directions opposite to the wind; e.g. left turns are difficult for winds on the starboard beam. Higher ship speeds not only improve ship controllability with respect to the wind but also make it easier to negotiate turns in high cross currents.

5. Vessel size is not a primary variable affecting track-keeping capability; the 80K and 400K vessels held track about equally well. The ratio of rudder area to immersed profile area of the hull appears to be an important physical factor.

3.6 RECOMMENDATIONS

1. Trim rudder curves for various wind conditions are useful for predicting wind conditions at which vessel track-keeping capability becomes marginal. It is recommended that additional research and development effort be expended to develop accurate and meaningful static and dynamic response curves for various types of vessels. These data could be used by masters or VTS personnel to determine whether it is safe to operate under specified conditions.

2. Additional research be conducted on handling of vessels under various environmental conditions (current and wind) with the goal of defining a typical range of responses of human pilots. These data would be useful for defining off-line piloting algorithms.

SECTION 4

OFF-LINE FAILED EQUIPMENT

4.1 INTRODUCTION

This section describes the results of the off-line study of the equipment failure runs studied at CAORF. The two types of equipment failures considered were:

- Engine failure (rudder still working)
- Combined engine/rudder failure.

4.1.1 Tug Support

During the engine failure conditions, no tugs were used. This is consistent with the objective of this set of runs which was to determine the ability of a ship to steer after the loss of engine power. The quality of such steering can be one of the factors in determining whether there should be a requirement for tug support.

During the engine/rudder failure conditions, tug support was available. 0, 2 or 4 tugs were used to examine their effectiveness in reducing ship advance and transfer. For ships between 40,000 and 120,000 DWT, each tug was a 5,000 H.P. vessel. For ships between 165,000 and 280,000 DWT, each tug was a 7,200 H.P. vessel. The tug backing forces available for each ship and the methodology of operations were discussed in paragraph 2.3.2.

4.1.2 Plots of Failed-Equipment Run

Section 4 of this report contains selected ground track plots of maneuvers performed by various ships which were subjected to casualties in the off-line studies. The prevailing environmental conditions, ship size and speed through the water are described in the top margin of each plot. The ship outline is drawn to scale, but the rudder size is

exaggerated. However, rudder position is accurate. The plot frequency is one per minute and the origin is located at the point x = 50,000 ft and y = 50,000 ft. All failure runs begin with the ship's center of gravity located at the origin. Off-line failure runs were begun with the ship in a state of approximate equilibrium and, although the ship heading might deviate from 000^{o}, the course made good in all cases is due north.

4.2 ENGINE FAILURE RUNS (No Tugs Available)

When an engine failure occurs just as a ship is commencing a turn, the tendency of the vessel to slow down due to lack of propulsion will be aggravated by the increased drag of the rudder and hull during the turn. The progressive speed loss has two major effects on the control of the vessel:

1. It continuously reduces the capability of the vessel to overcome the wind forces and moments exerted on it until, finally, the vessel will luff into the wind regardless of the rudder control being applied.
2. It continuously reduces the ability of the vessel to stem the tide. The vessel must point up at increasingly higher angles to offset a cross current, as its speed through the water decreases. When its speed through the water decreases to the speed of the tidal current, its rudder effectiveness is zero, and the ship must anchor or it will drift backward with respect to the ground.

With no tugs available it is obvious that after some period of time, unless the vessel can drop an anchor, it will eventually go out of control and be at the mercy of the elements. Therefore, the purposes of these runs were to:

- Determine whether a ship which had suffered an engine failure, but still had rudder available, could successfully turn and/or remain under control within the con-

fines of a channel for an appreciable time. This time might be useful for overcoming some types of engine failure or it might provide sufficient time for tugs in escort to tie up and guide the vessel, thereby avoiding a grounding.

- Determine whether the speed over the ground can be brought to a safe anchoring speed (approximately ½ knot or less for large tankers).

The conditions under which the runs were made are summarized in paragraph 2.3.1.

4.2.1 Run Methodology

Initially the ship is navigating a channel in a state of approximate equilibrium at a given speed through the water and in the presence of wind and current. The pilot commands a right turn of some specified magnitude, and at that instant the engine fails. The pilot has a number of options available to him. As soon as the pilot realizes that the engine has failed he can:

1. Try to maintain his intended track as best he can while the ship's speed through the water decreases.
2. Immediately turn up into the current in any attempt to slow the vessel to a low enough speed over the ground to permit an anchor to be dropped. For a following current, a reversal of the initial course is necessary.

Strategy number one above was first simulated in the off-line runs by the following technique:

The initial 50% of the turn was made with a fixed 15° or 25° right rudder. The final 50% of the turn was made by turning over control to a heading-sensing autopilot, which brought the ship to the desired heading. The use of a heading-sensing autopilot did not result in satisfactory turn maneuvers under strong tidal current

conditions (See Figure 4-1). Data gathered under these conditions were of limited value for several reasons: the heading-sensing autopilot is sensitive only to the difference between actual and desired heading. It is oblivious to a buildup of the transfer and advance to "unreasonable" levels. It does not react reasonably when the vessel is being carried away by the current; i.e., the autopilot continues to attempt to achieve the desired heading whereas a human pilot would probably sense the situation and attempt to overcome the drift by turning up into the current. Also in many cases, the ships did not turn well because of adverse wind conditions and never achieved appreciable heading change. In such a case, a pilot, sensing the poor rate of turn, would undoubtedly have ordered hard over rudder (35^o) rather than maintain the 15^o or 25^o rudder programmed into the off-line simulation.

It is interesting to note that in the runs made with a head-on current and the heading-sensing autopilot, although the vessel reversed its direction of motion with respect to the ground (Figure 4-1), the speed over the ground often did not go much below 3 knots. This speed is much too high for anchoring to be attempted.

The results obtained with heading-sensing autopilot suggested certain improvements in the off-line simulation and additional runs were made with failed engine and either:

- a hard right rudder in the presence of a following current, or
- a track-keeping autopilot in the presence of a head-on current.

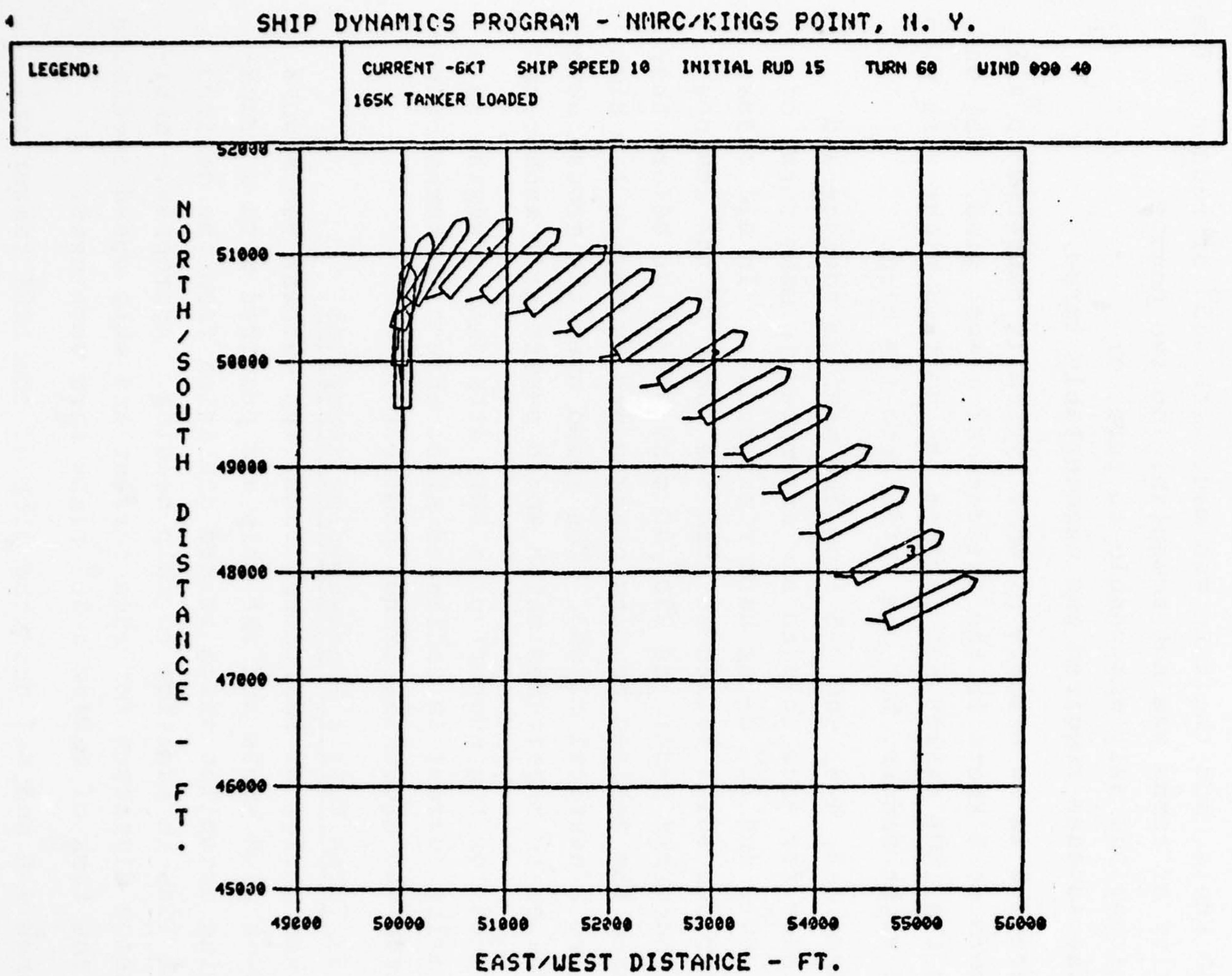

Figure 4-1. Typical Off-Line Failed Engine Run With 6-kt Current, Initial Speed 10 kts, 15° Rudder

4.2.2 Turns With Hard Right Rudder (-35°)

In this series of additional runs, the current was always fair (following) at +6 knots, the winds were 270° and 090° at 40 knots, and the turn was made with -35° of rudder. The quality of turns was not acceptable on two counts:

- either the ship was unable to turn, or
- the advance required was unacceptably large.

Figure 4-2 is an example of what typically happened to all tankers at 4 knots in the presence of a west wind. Not only does the 120K tanker not perform the desired right turn with hard right rudder, but she luffs into the wind.

Figures 4-3, 4-4, and 4-5 show the maximum advance and transfer for each ship as she attempted to make turns of 30°, 60°, and 90° using hard right rudder. In all cases, either the ships failed to make the turn, or the advance that occurred under the $270^{\circ}/40$ wind condition before they reached the desired heading changes was excessive (as high as 1 to 2 nautical miles). The speed over the ground never decreased to magnitudes which would permit safe anchoring.

The need for tug support of a ship with failed engine in a following current is indicated since effective turns cannot be made and anchoring is not possible.

4.2.3 Turns With a Track-Keeping Autopilot

In this series of additional runs, the current was always head-on at 6 knots and the ship was provided with a track-keeping autopilot which sensed deviation from the desired track line in addition to ship heading. Appropriate anticipation distances for each current and ship speed condition for the task of making a 30° right turn were used.

Figures 4-6 and 4-7 show the plot of the 120K tanker attempting to make a 30° turn with east and west winds, respectively, in the presence of a 6-knot head-on current.

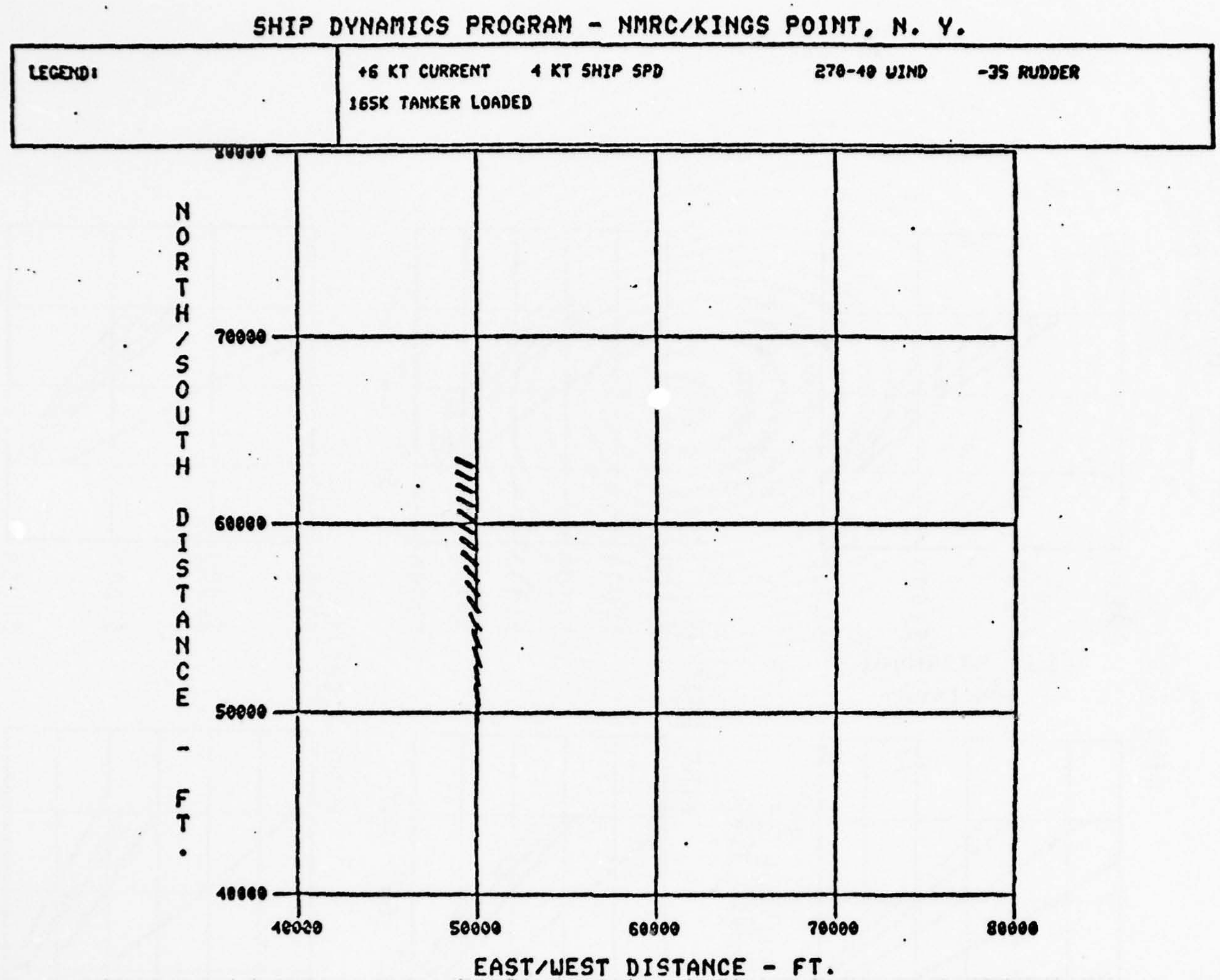

Figure 4-2. Typical Off-Line Failed Engine Run With 6-kt Current, Initial Speed 4 kts, Hard Right Rudder

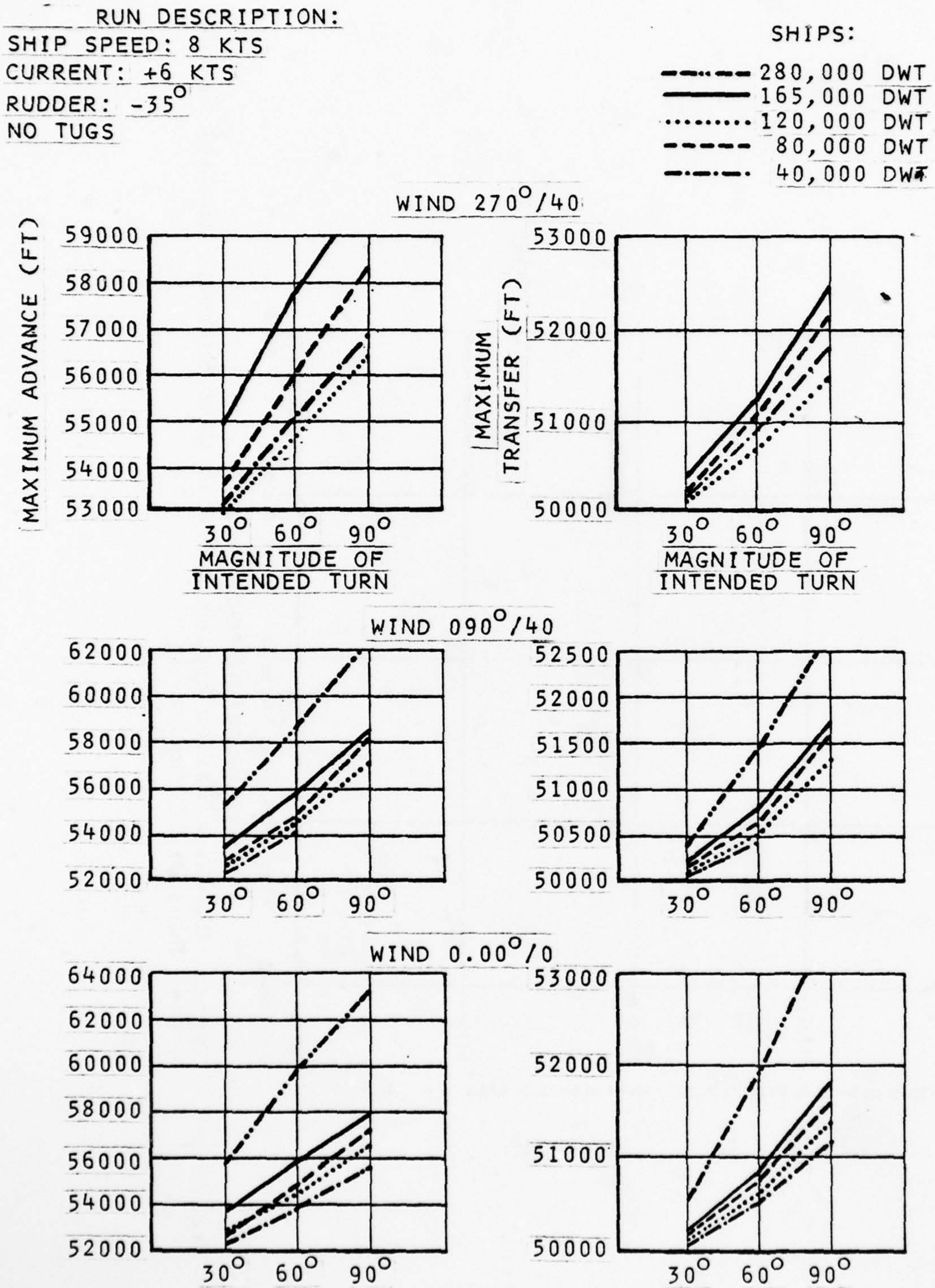

Figure 4-3. Advance and Transfer During Hard Right Rudder Turns, Failed Engine Runs, Initial Speed 8 kts

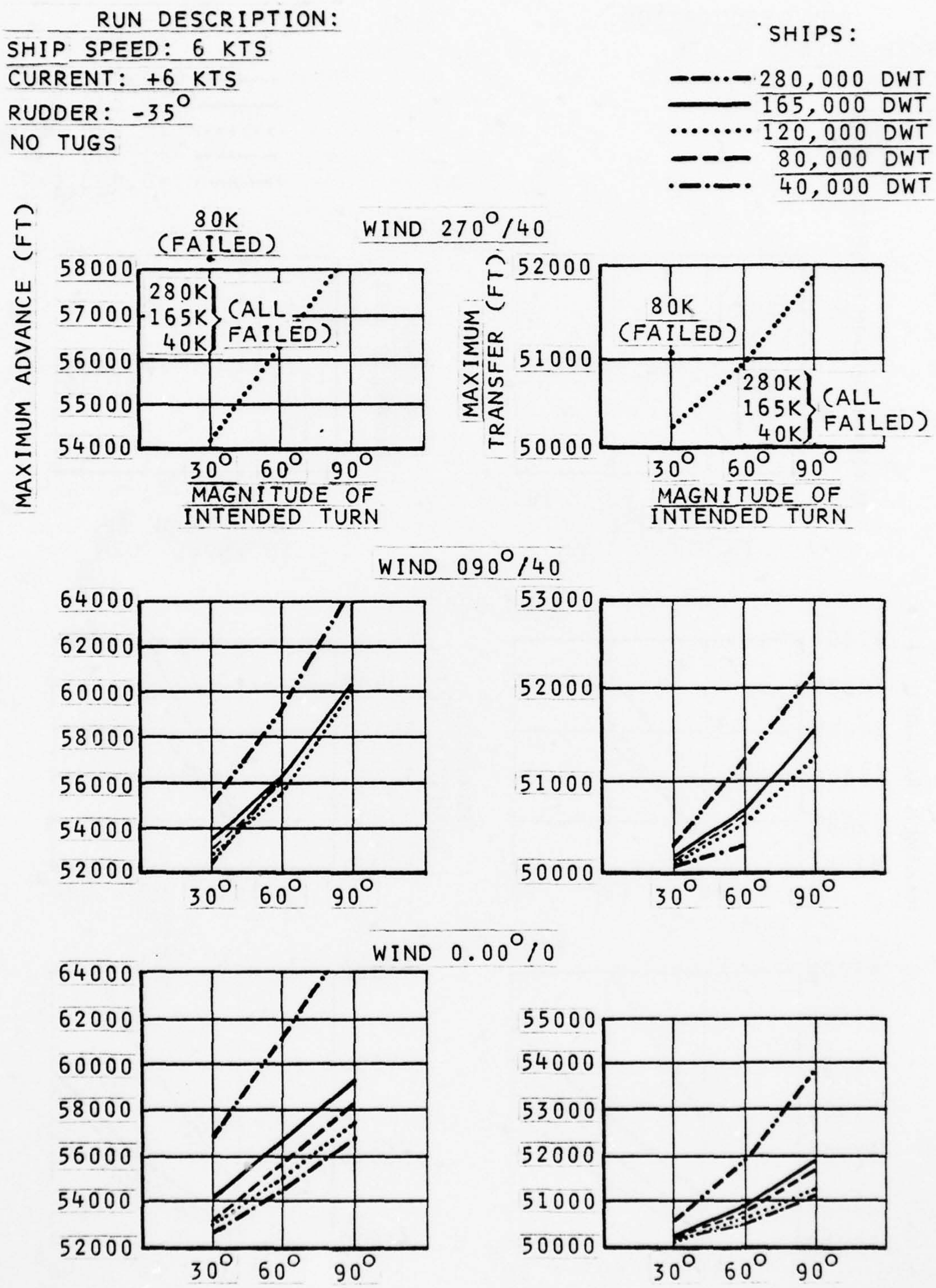

Figure 4-4. Advance and Transfer During Hard Right Rudder Turns, Failed Engine Runs, Initial Speed 6 kts

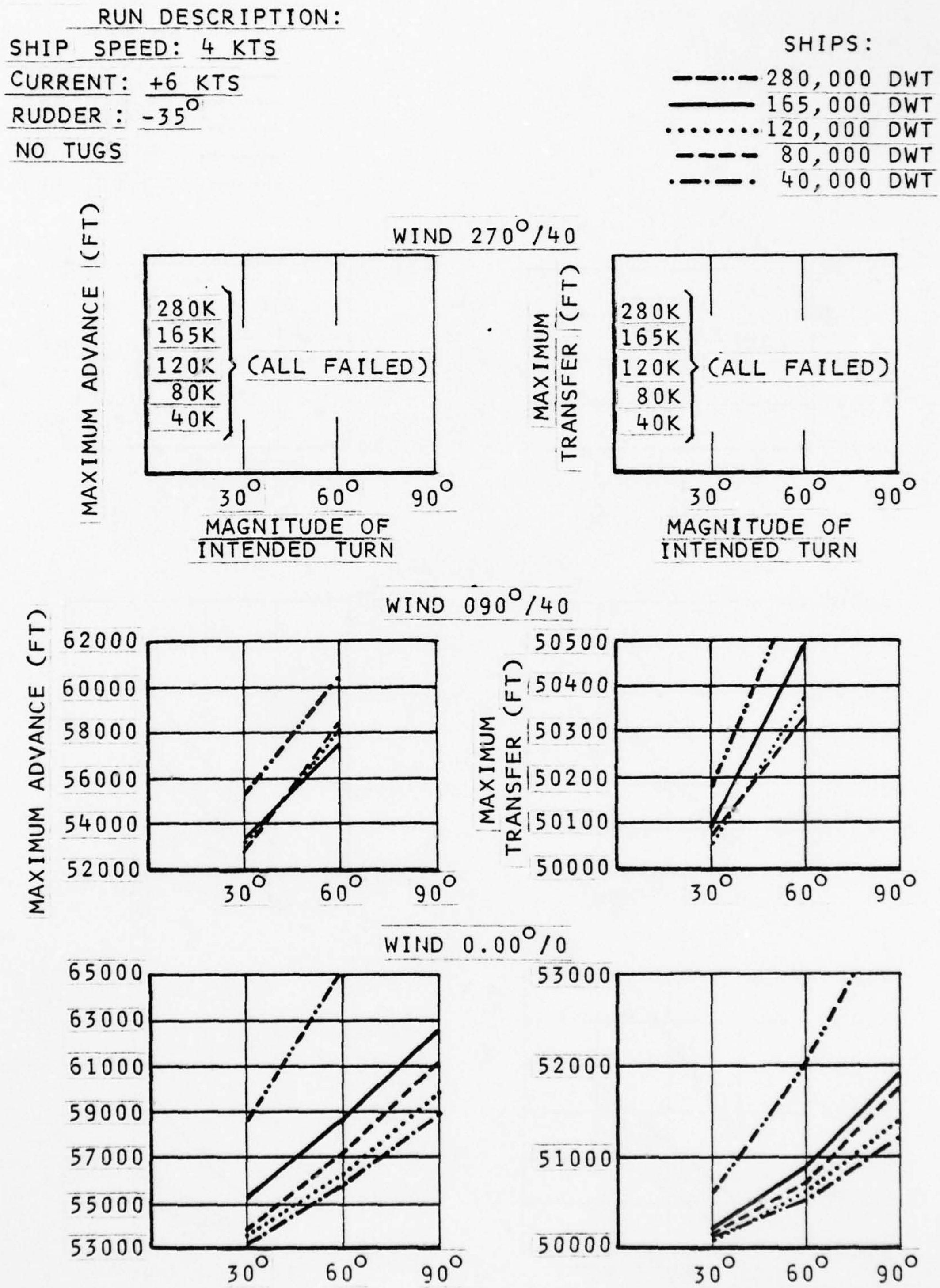

Figure 4-5. Advance and Transfer During Hard Right Rudder Turns, Failed Engine Runs, Initial Speed 4 kts

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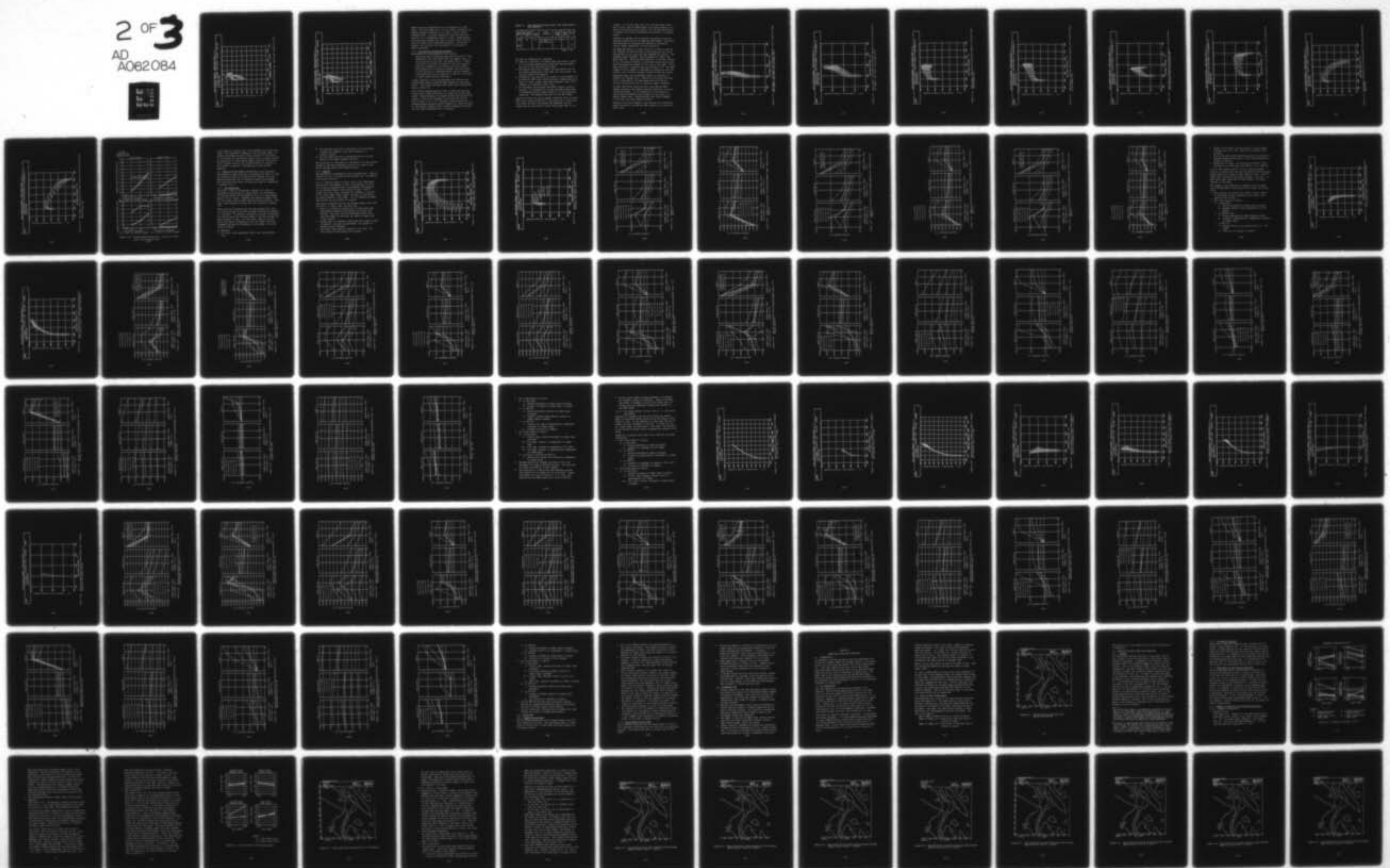

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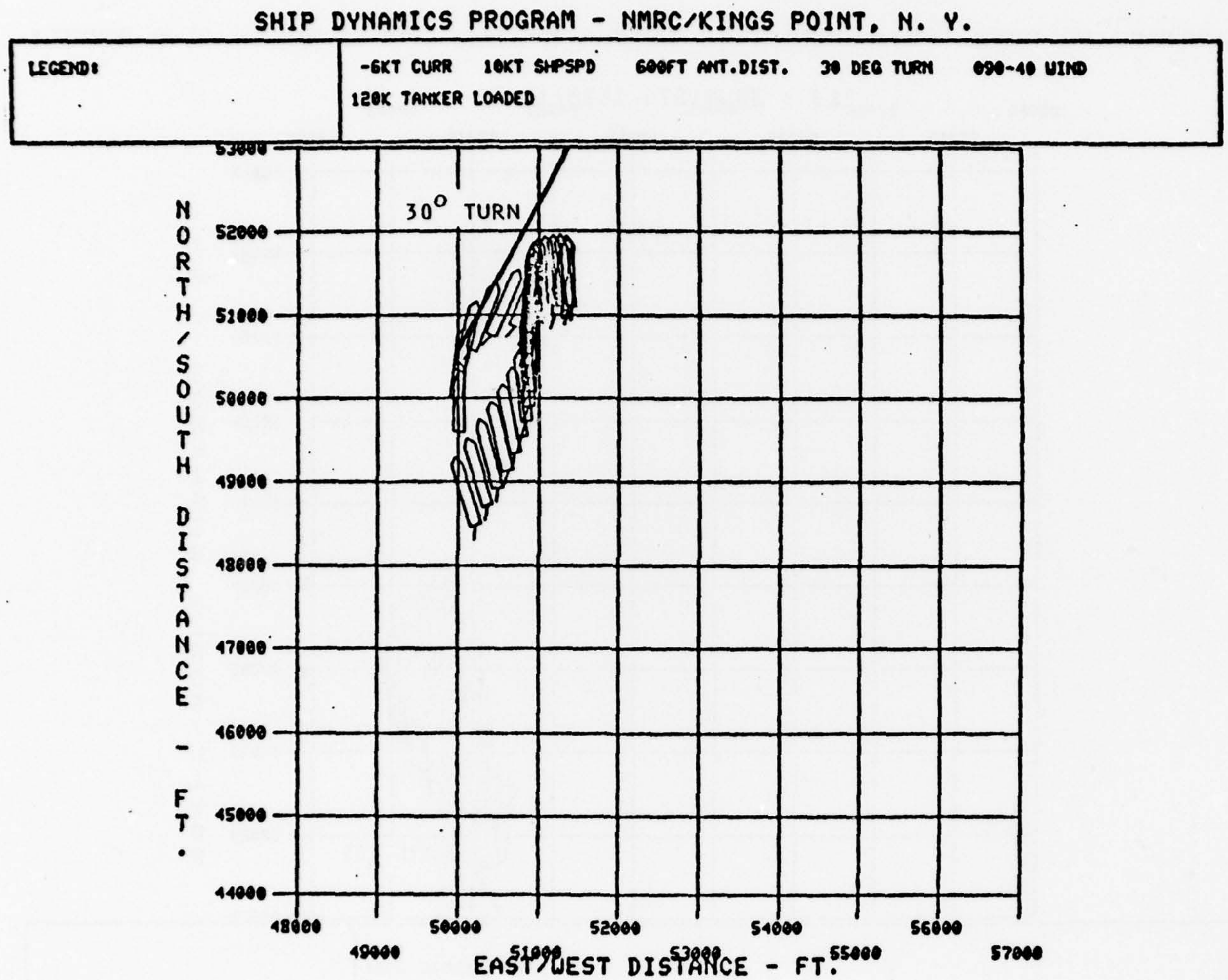

Figure 4-6. 120K Tanker Failed Engine Run, East Wind, Head-On Current

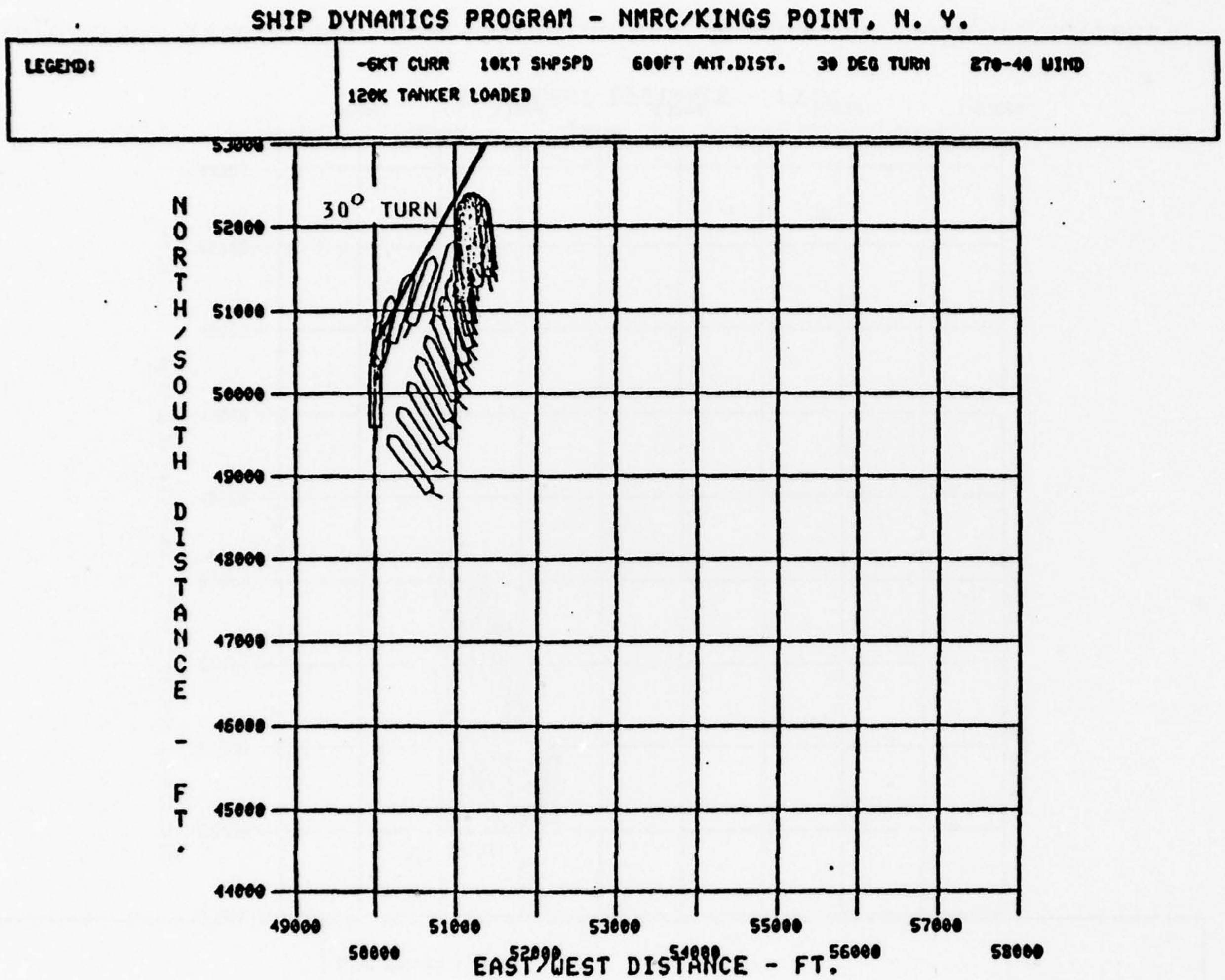

Figure 4-7. 120K Tanker Failed Engine Run, West Wind, Head-On Current

These plots are representative of the behavior of other ships. The turns begin well, but the vessel overshoots the heading needed to maintain it on track. After a slight backward drift, it points toward the track and holds its position for a considerable amount of time. Approximately 15 minutes pass between the time of engine failure and the time the vessel drifts backward helplessly. For several minutes, the velocity over the ground is low enough to permit anchoring.

4.2.4 Turn-Up-Into-The-Current Maneuver

The scenario for this maneuver is as follows:

> The second option mentioned previously would be to turn immediately into the current when the engine fails. At the initiation of the turn, the engine fails. A short time later the bridge is alerted to this fact and the autopilot attempts to turn back up into the current. This hopefully will maintain steerage, use the current to slow the ship to anchoring speed, and buy precious time during which a tug might get a line up to the ship or engine power might be restored.

A small sampling of runs incorporating this maneuver was accomplished using the 80K and 280K tankers to test feasibility. The conditions under which these runs occurred are shown in Table 4-1.

The following methodology was used: a right turn was initiated with a rudder deflection of either 15° or 25° right rudder. Simultaneously, the engine failed and the ship continued to turn in the presence of the wind and current. After a delay of 2, 3, or 4 minutes, control was given to a heading-sensing autopilot which attempted to return the ship to the original heading (000°) thereby stemming the current. All runs were terminated after 15 minutes.

TABLE 4-1. OFF-LINE FAILED ENGINE RUNS (SHIP TURNS BACK UP INTO CURRENT)

Ship Type	Ship Speed Thru Water (kts)	Current (kts)	Wind Condition	Initial Rudder (Deg)	Time Delay (Min)	No. of Runs
80K	10	-6	270° @ 40 kts and 090° @ 40 kts	15°, 25°	2,3,4	12
280K						12
					Total:	24

The results indicated the following:

- Under all conditions, the 280K tanker was able to return to its original heading more often than the 80K tanker, and also to hold her position longer.
- The greater the initial rudder, and the greater the delay before attempting to turn back into the current, the less successful the maneuver.
- Attempts to turn back into the current in the presence of an easterly (90°) wind (which produces a moment adding to that of a right rudder) were less successful than in the presence of a westerly (270°) wind.
- If the engine failure were discovered rapidly (within 2 minutes), it was possible to bring the 280K tanker down to anchoring velocity under almost all of the conditions simulated. The opposite was true for the 80K tanker.

Figures 4-9 and 4-13, which display 15-minute plots for each ship, give a good indication of the effect due to ship size; the larger the ship, the greater her momentum, and the longer she can hold herself before being swept away by the

current. It is also true that since the 80K tanker turns more quickly than the 280K tanker, she places herself at an angle to the current more quickly (for the same application of rudder) and is thus affected by the current to a greater extent.

Figures 4-8 through 4-15 illustrate the ground tracks for selected conditions for the 280K and 80K tankers. The plots were selected to illustrate the effects of time delay, initial rudder deflection, and wind direction.

The 280K DWT tanker in a west wind with a 2-minute time delay (Figures 4-8 and 4-9) does a very effective job of reversing the initial turn rate and stemming the current. The maximum lateral transfer, with 25 degrees of rudder, was about 800 feet. When the wind comes out of the east (Figure 4-10), the lateral transfer is increased significantly since the wind assists the vessel in its turn to the right. For a west wind with a 4-minute time delay (Figure 4-11), the 280K tanker is still capable of successfully turning up into the current, but a lateral transfer of about 2,200 feet occurs.

Comparable data for the 80K DWT tanker are presented in Figures 4-12 through 4-15. Under both wind directions and for all time delays, the 80K tanker does not stem the current as effectively and it achieves larger transfers.

At some time before astern motion of the 80K and 280K tankers occurred, the vessels achieved relatively low over-the-ground speeds. If the capability for obtaining accurate speed information were present on each ship (e.g., Doppler speed logs), anchoring might have been attempted at the time that these speeds occurred.

Figure 4-16 contains graphs of the minimum over-the-ground speed attained by the 80K and 280K tankers as a function of delay time.

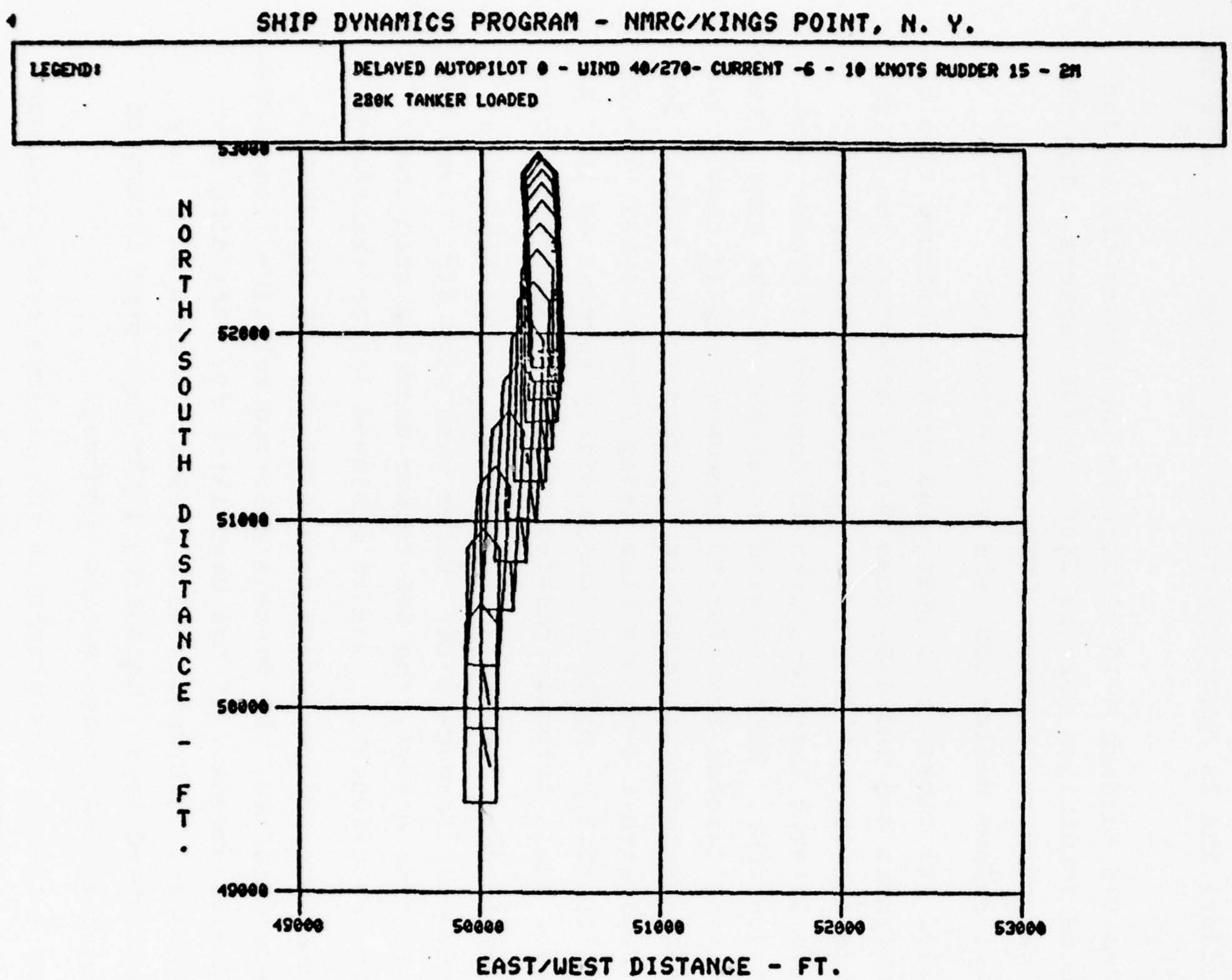

Figure 4-8. 280K Tanker, Turn-Back-Into-Current Maneuver after 2-minute Delay, 15° Rudder, West Wind, Failed Engine Run.

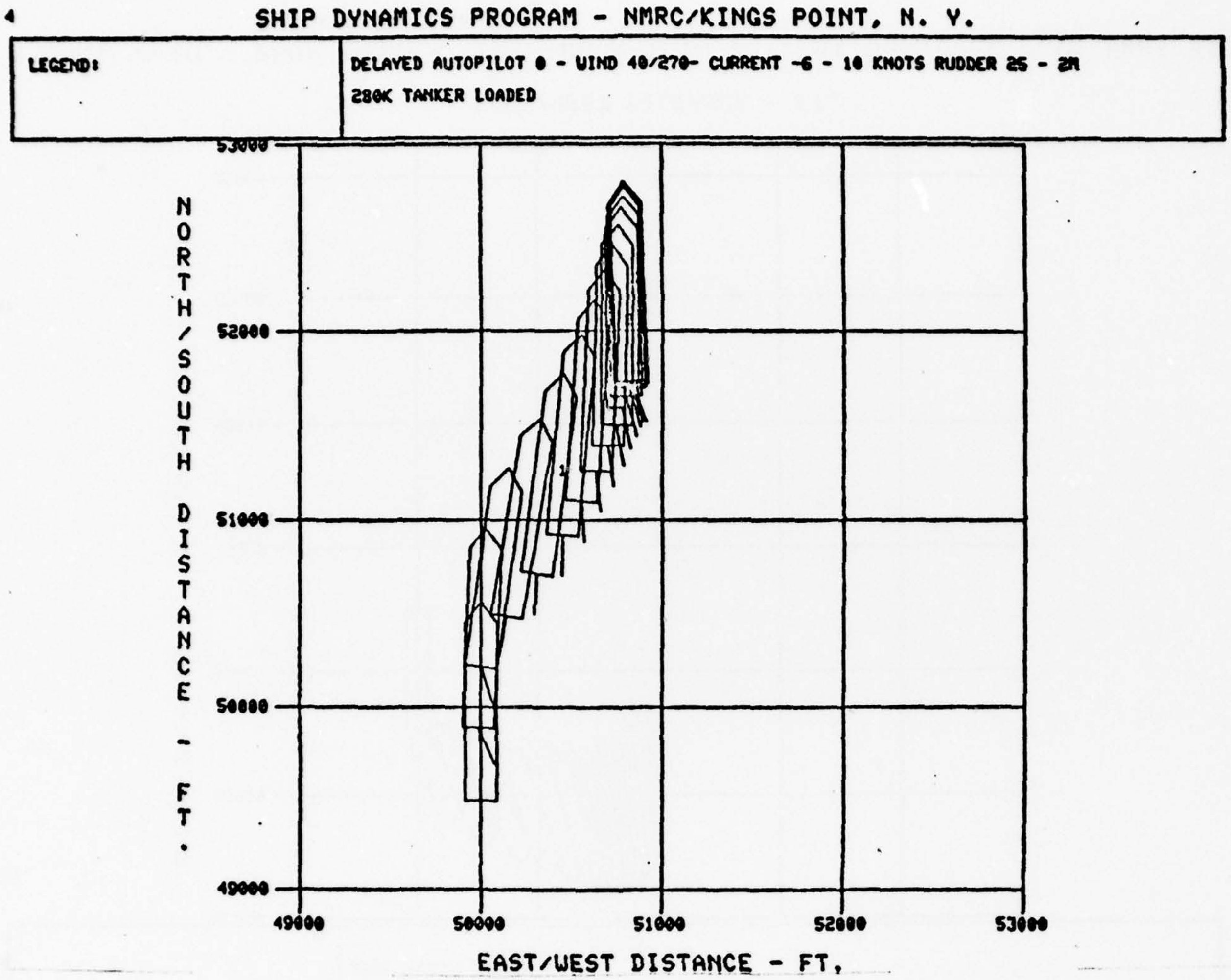

Figure 4-9. 280K Tanker, Turn-Back-Into-Current Maneuver after 2-minute Delay, 25^{o} Rudder, West Wind, Failed Engine Run.

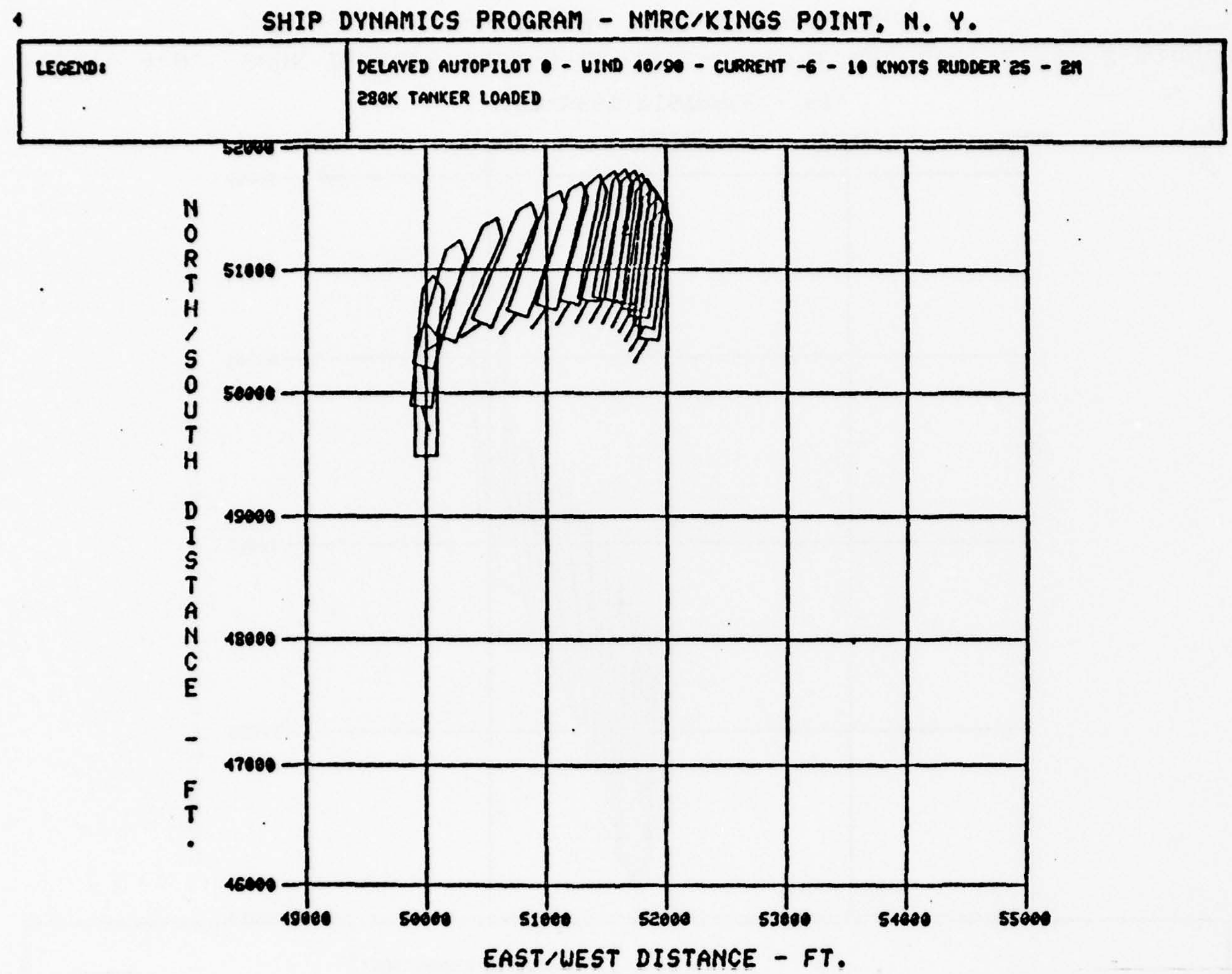

Figure 4-10. 280K Tanker, Turn-Back-Into-Current Maneuver with East Wind, Failed Engine Run

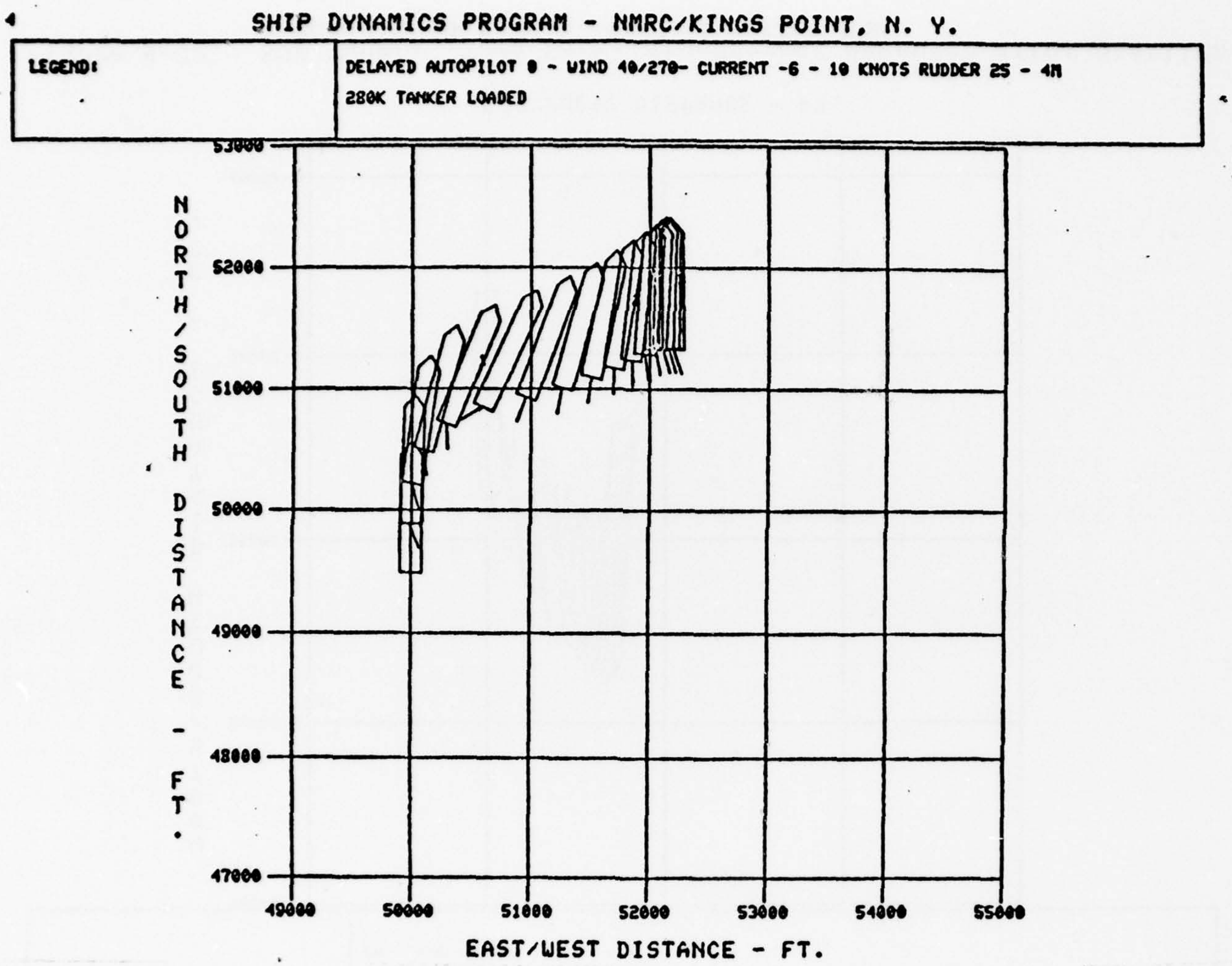

Figure 4-11. 280K Tanker, Turn-Back-Into-Current Maneuver with 4-minute Delay, Failed Engine Run

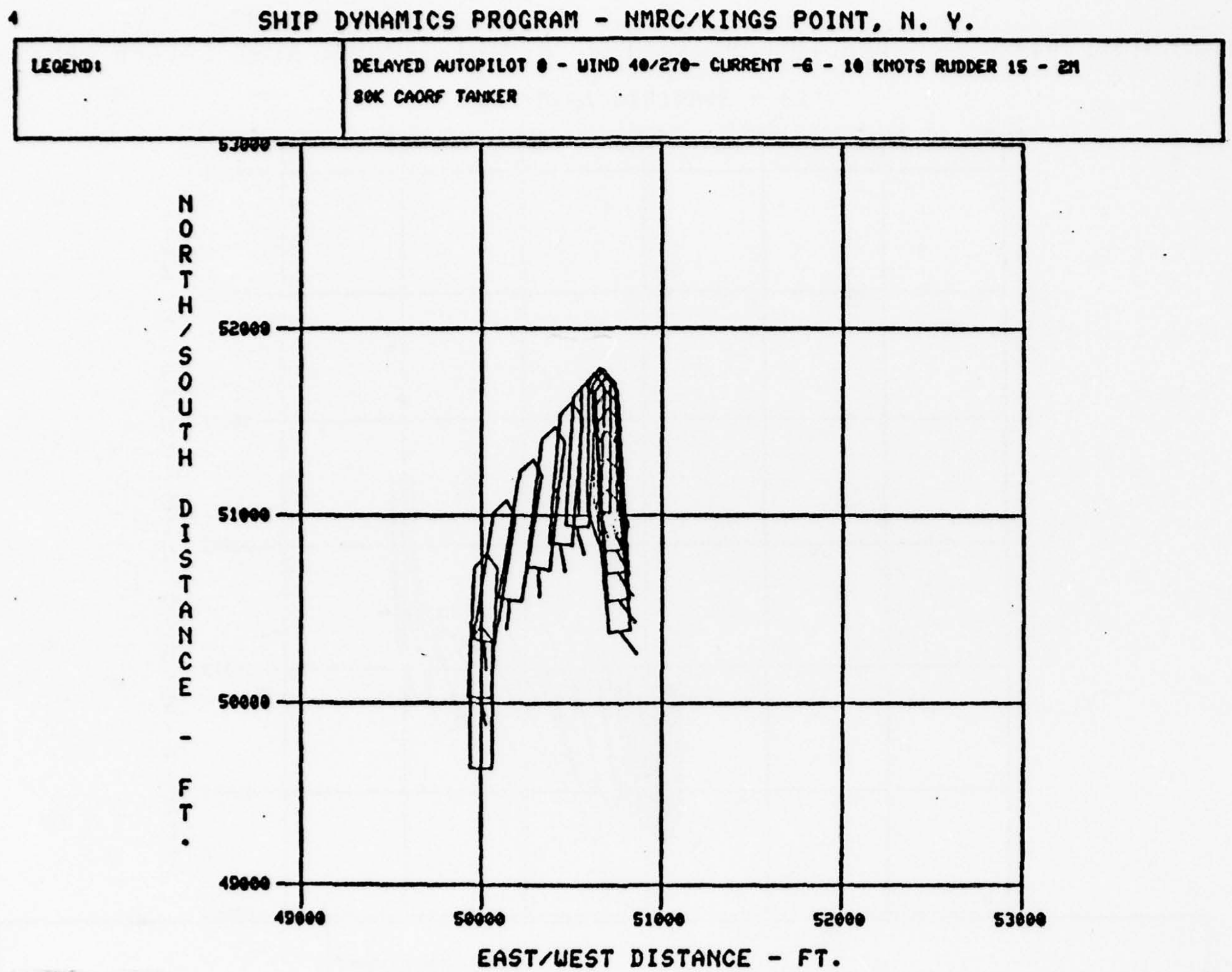

Figure 4-12. 80K Tanker, Turn-Back-Into-Current Maneuver after Starting Reduced-Rudder Turn, Failed Engine Run

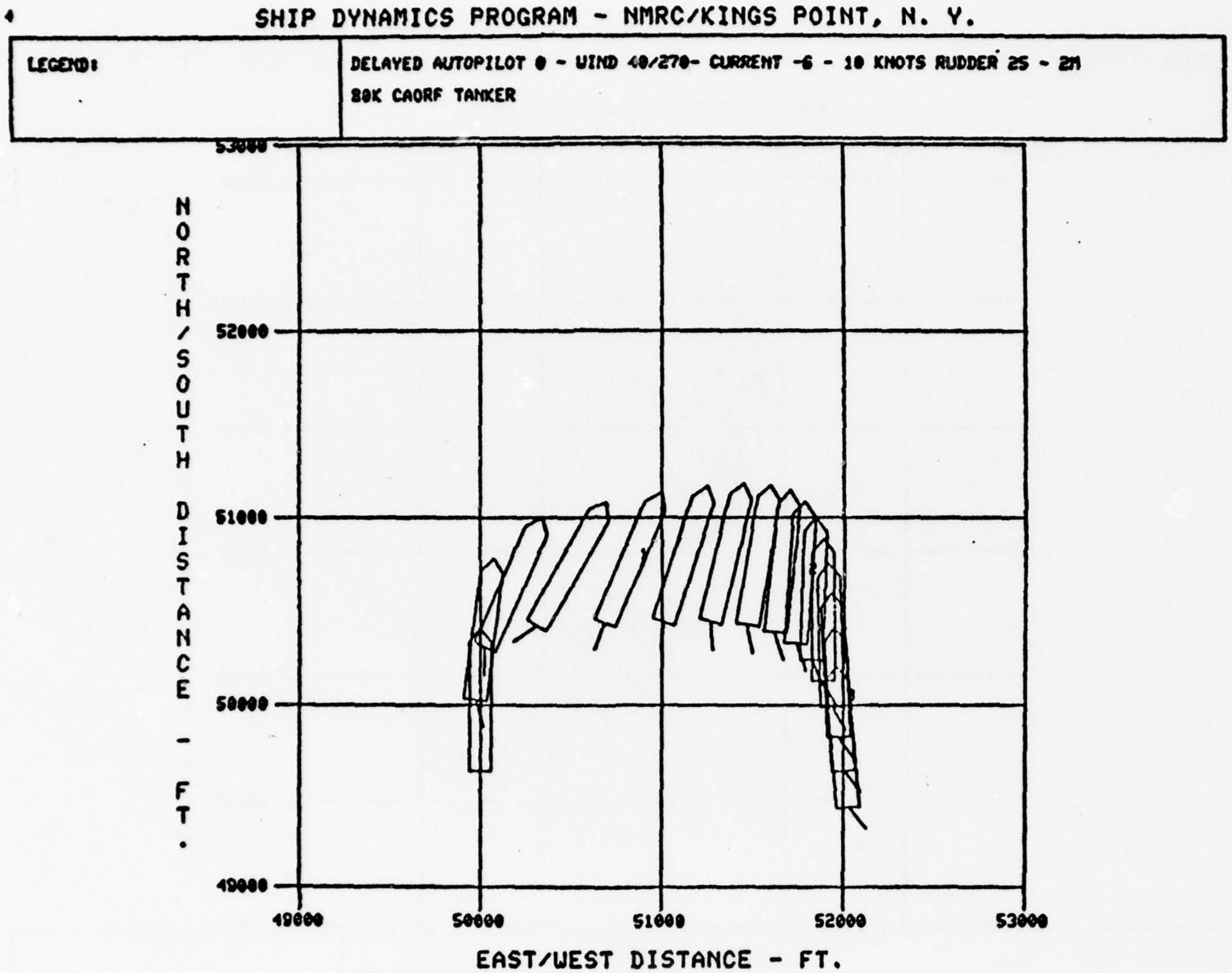

Figure 4-13. 80K Tanker, Turn-Back-Into-Current Maneuver, Failed Engine Run

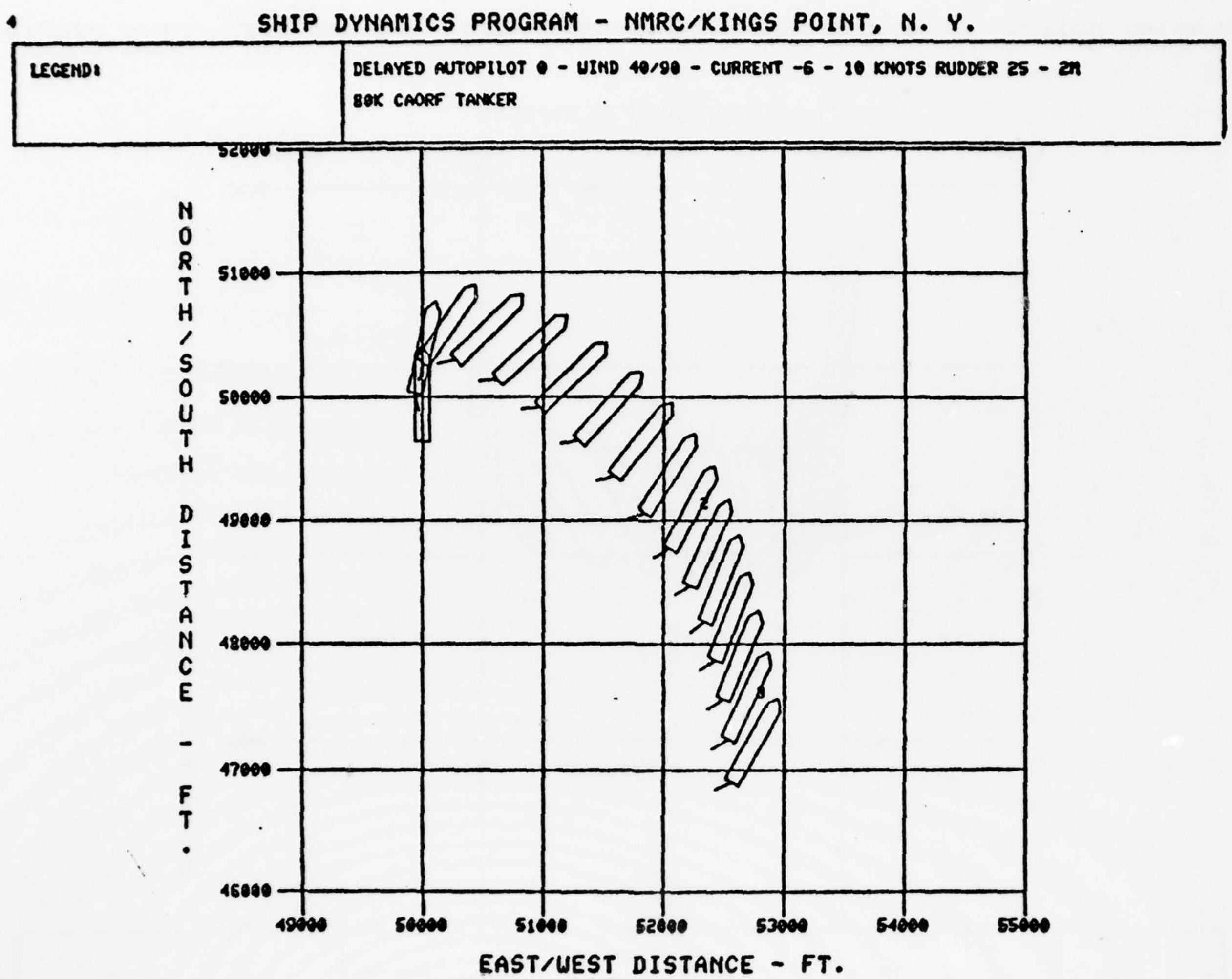

Figure 4-14. 80K Tanker, Turn-Back-Into-Current Maneuver with East Wind, Failed Engine Run

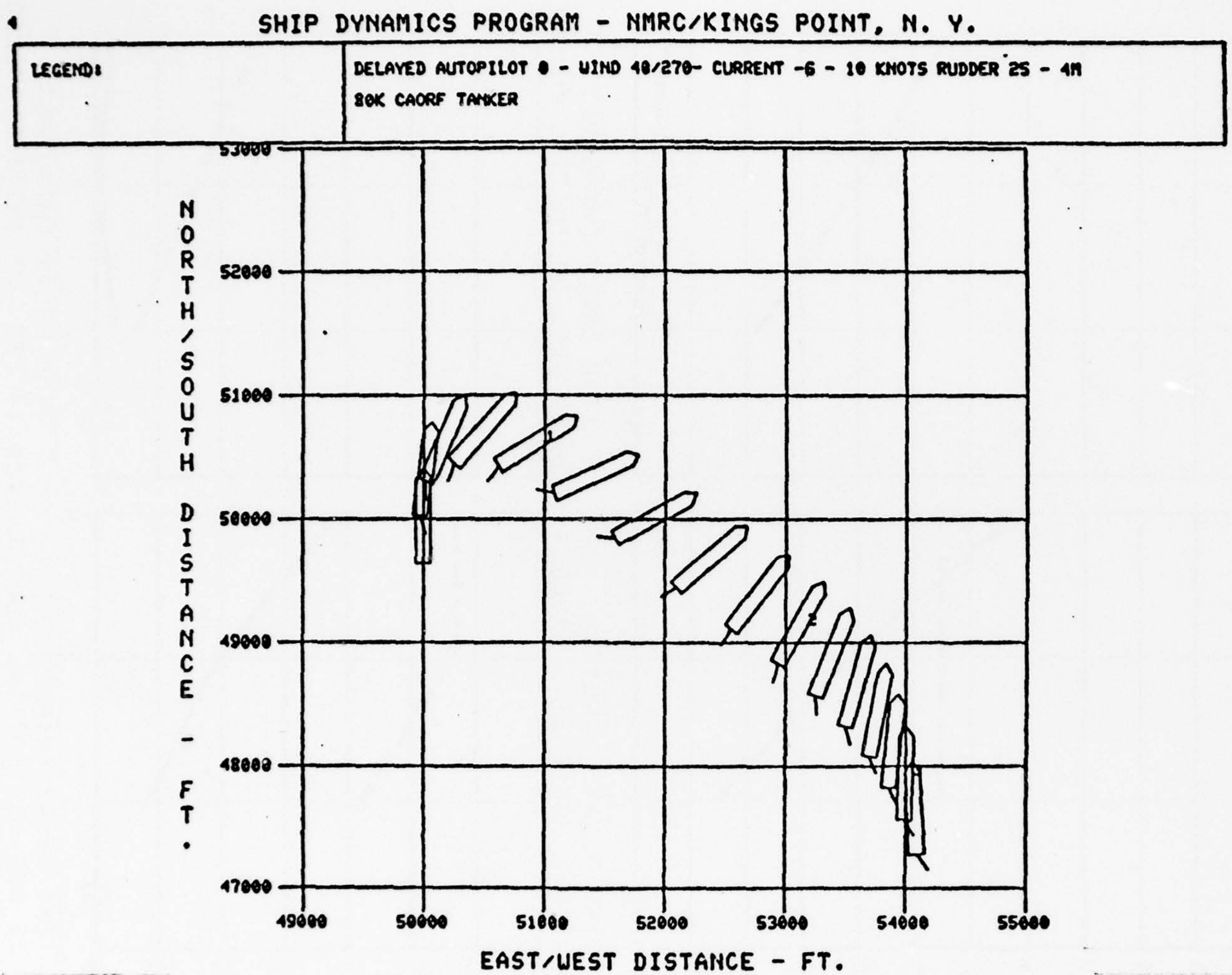

Figure 4-15. 80K Tanker, Turn-Back-Into-Current Maneuver with 4-minute Delay, Failed Engine Run

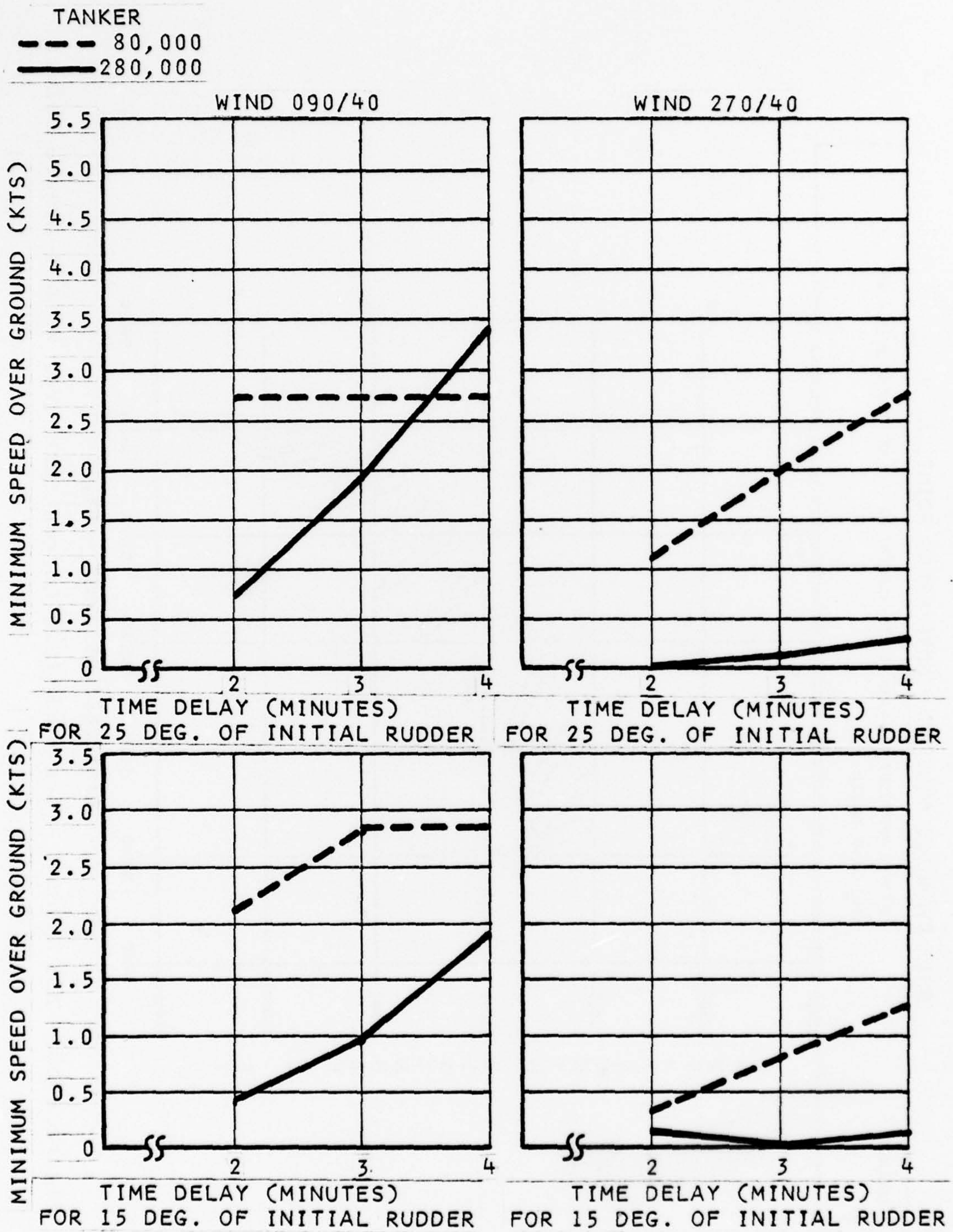

Figure 4-16. Minimum Speed Attained as a Function of Time Delay, Failed Engine Runs

It is clear at a glance that in the presence of an east wind (090^{o}), the advantage is generally with the 280K tanker although the minimum values of speed increase for both ships. It is evident that obtaining a timely alert to engine failure and being able to sense ground speed accurately could prove to be of great value to the ultimate safety of the ship in any attempt to perform a "heading-up-into-the-current" maneuver.

4.3 COMBINED ENGINE/RUDDER FAILURE FUNS (Tugs Available)

The purpose of these runs was to determine the effect of tugs as retarding forces on the advance and transfer of a ship which had suffered loss of propulsive power and steering. The conditions under which the runs were made are summarized in section 2.3.2.

4.3.1 Run Methodology

Initially, a ship is navigating a channel in a state of approximate equilibrium at a given speed, in the presence of wind and current and attended by 0, 2, or 4 tugs already made up on soft lines. Suddenly the propulsive power fails and the rudder locks in some right deflection position. The tugs, after appropriate delay, are put in position backing full.

These runs were conducted with the tugs backing full until the fore/aft speed of the ship through the water was reduced to 0.25 knots. In addition, data were collected to determine the time at which the fore/aft speed of the ship through the water reached 1.0 knot. At that point, tugs in the real world could begin attempting to turn the tanker, and even disengage and hook up differently in an attempt to tow the vessel to safety.

To summarize:

1) All tugs, after appropriate delay, were used backing full.

2) The tugs were used only in multiples of 2 and created a drag force opposite to the ship heading (i.e., directly astern).
3) The runs ended and plots terminated when the fore/aft speed of the tanker reached 0.25 knot.

The following is a discussion of the behavior of the various tankers in the above described situation in terms of the ship's maximum advance and transfer values.

4.3.2 Results

The discussion is presented in the following order: head-on current (-6 kts.), followed by zero current (0), followed by fair current (+6 kts.).

4.3.2.1 Head-On Current (-6 kts.) and 10 kts. Ship Speed

The reader is encouraged to first study Figures 4-17 and 4-18 to gain an appreciation of the general form taken by all the ground tracks in this series of runs. With 0^{o} rudder and a west wind, the ships all transfer to the left. In all other cases (right rudder, and zero or east wind), the ships transfer to the right. All the tankers are swept away quickly by the current of -6 knots.

Referring to Figures 4-19 for the maximum advance and transfer with 0, 2, and 4 tugs, one sees that:

1. There is no effect on advance due to additional tugs. The maximum transfer occurs during the initial few minutes. The tugs, after the 90-second delay, have only just begun to back when the vessel is swept away by the current.
2. Larger ships are generally associated with larger values of advance. As ship size decreases, the values for maximum advance decrease.
3. Additional tugs diminish transfer in all cases, but with gradually diminishing effectiveness.

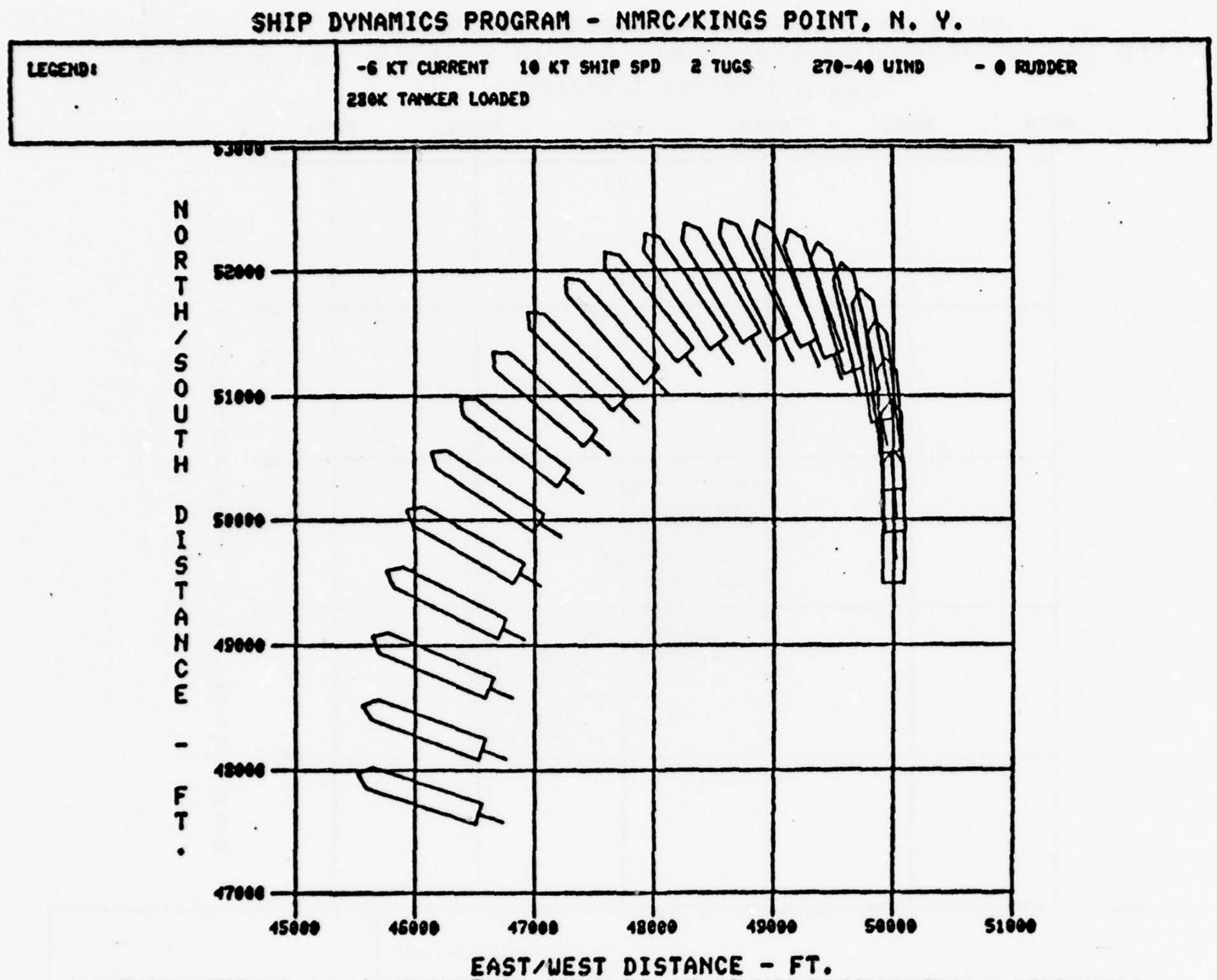

Figure 4-17. Typical Ground Track, Failed Engine/Rudder Run, 0^{o} Rudder, West Wind, Head-On Current

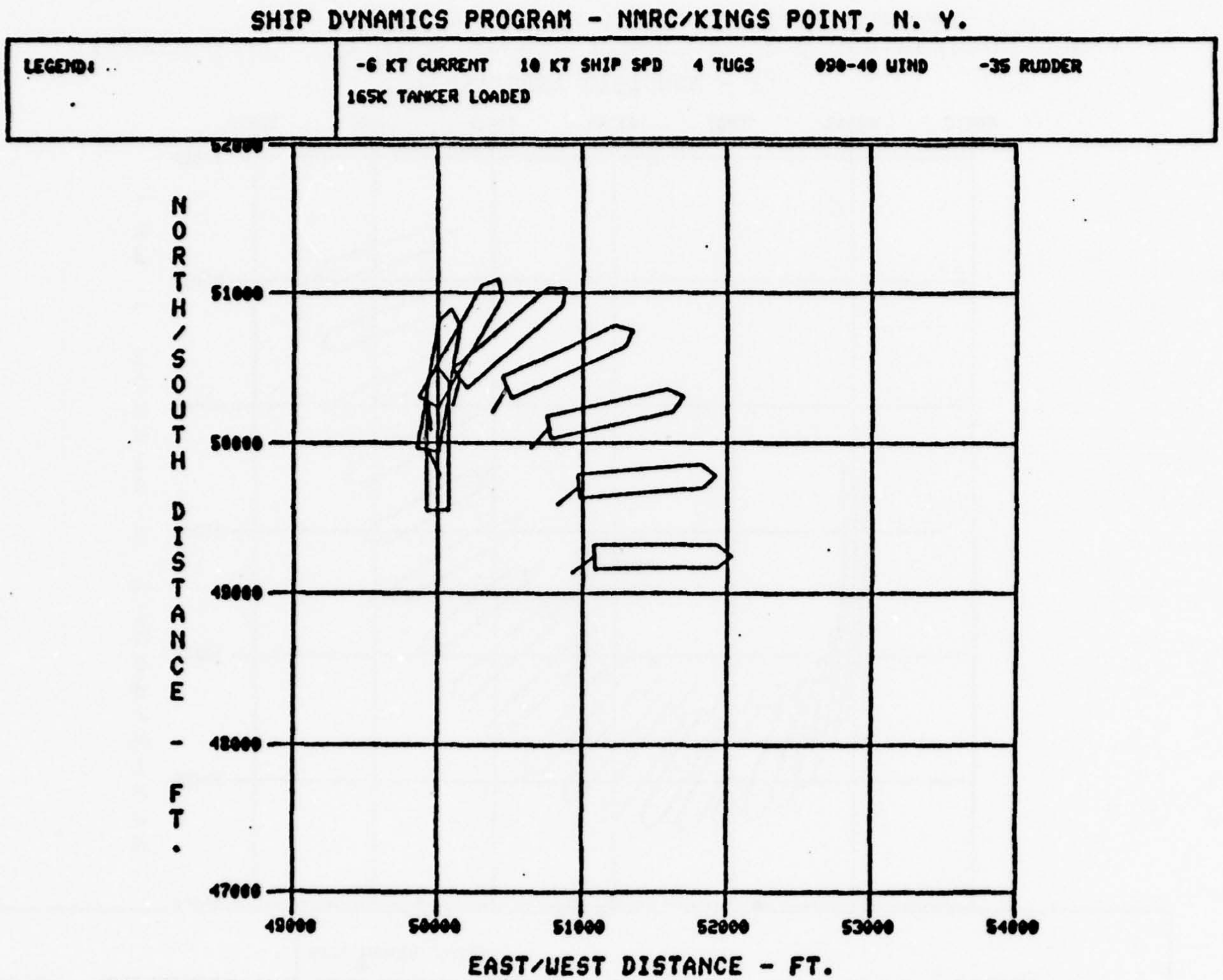

Figure 4-18. Typical Ground Track, Failed Engine/Rudder Run, 35° Rudder, East Wind, Head-On Current

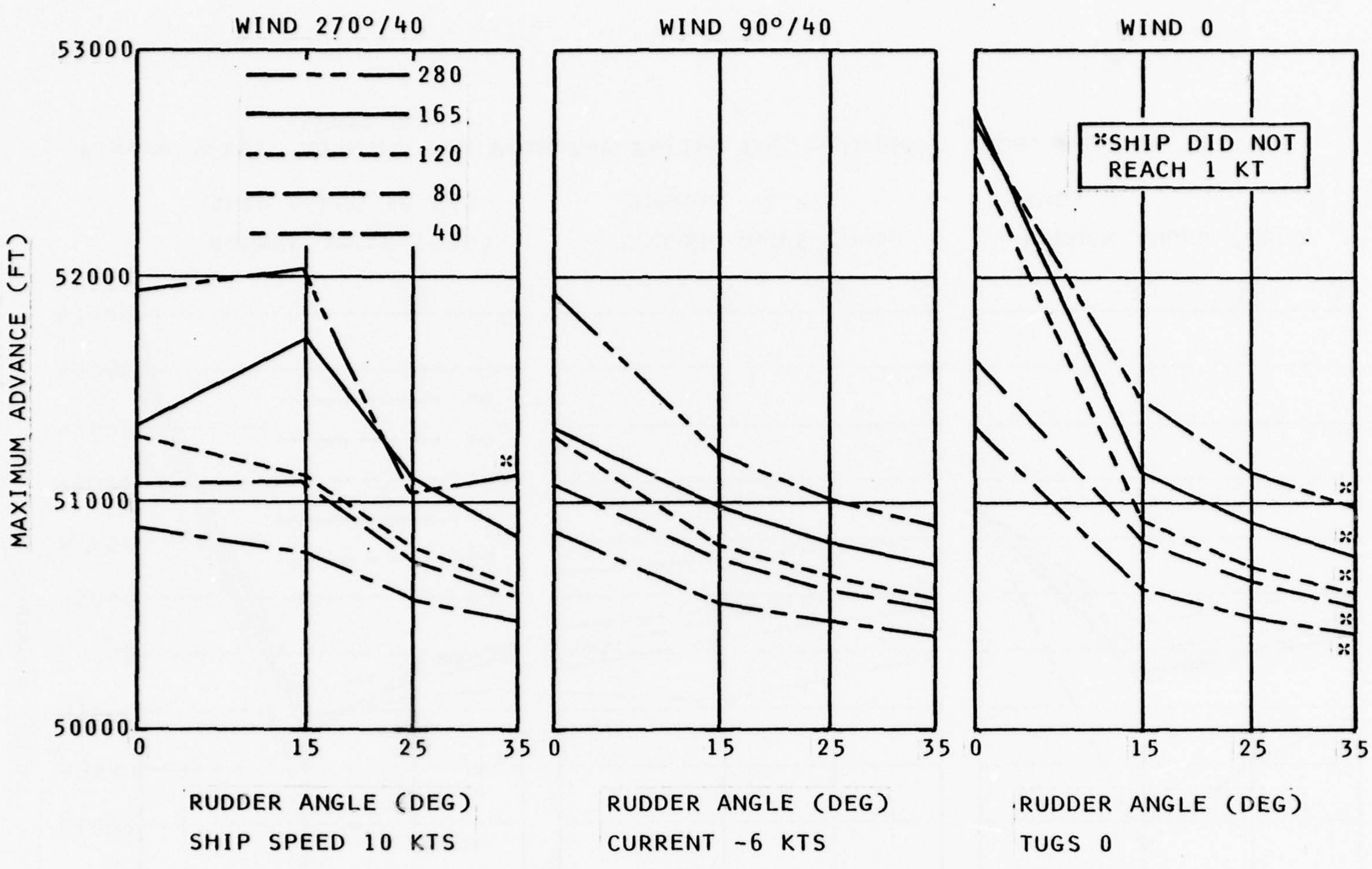

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 1)

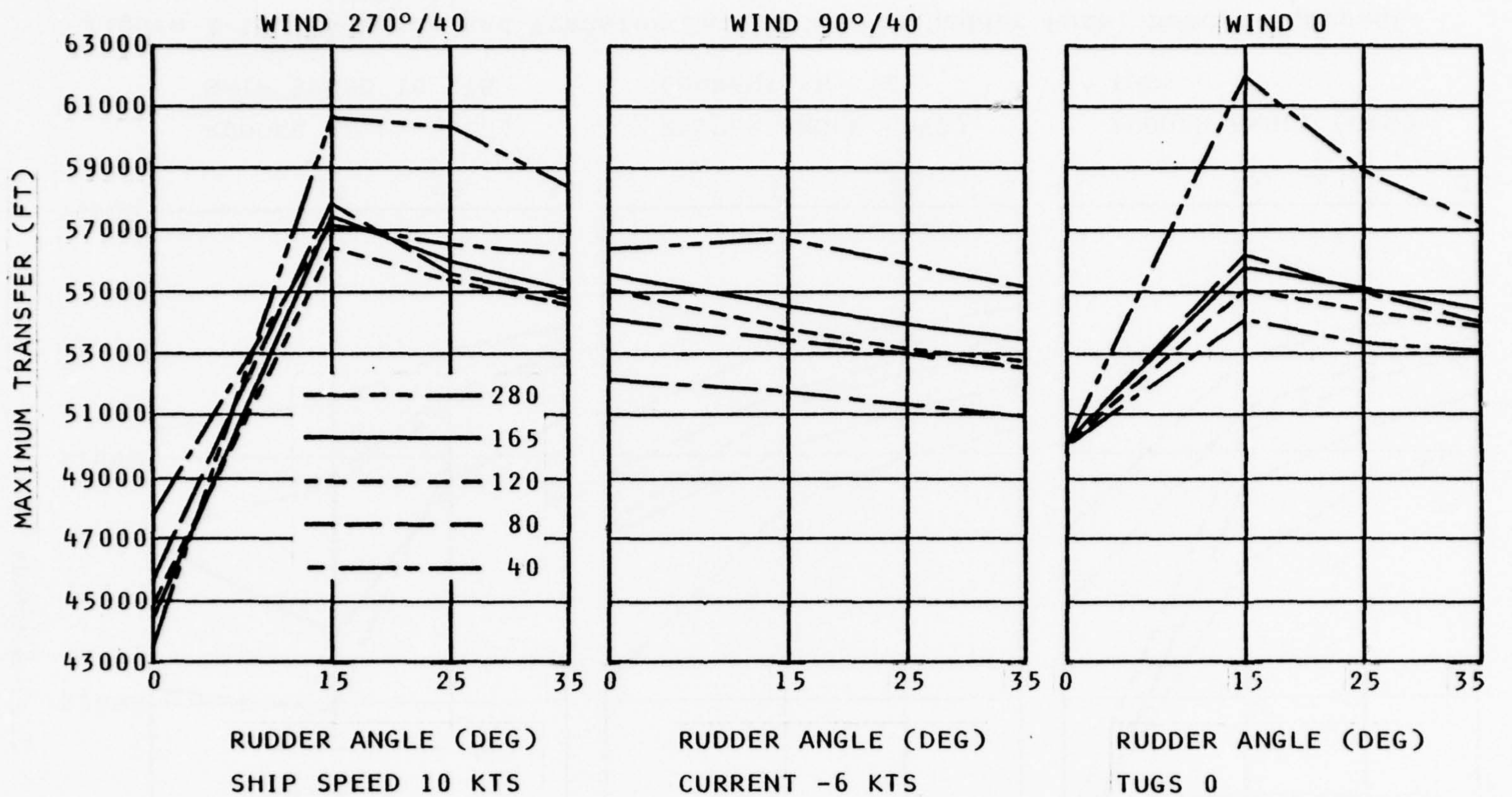

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 2)

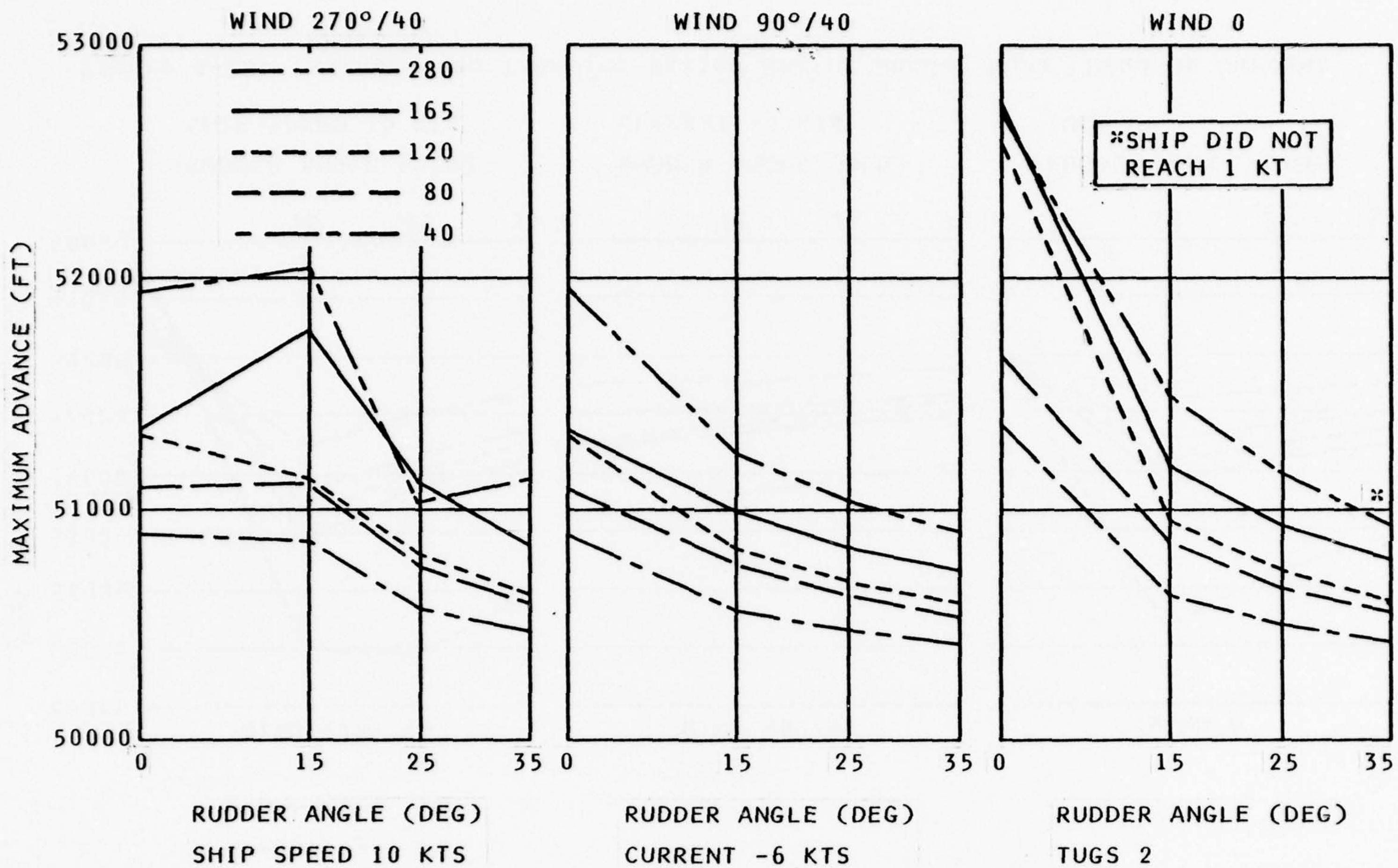

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 3)

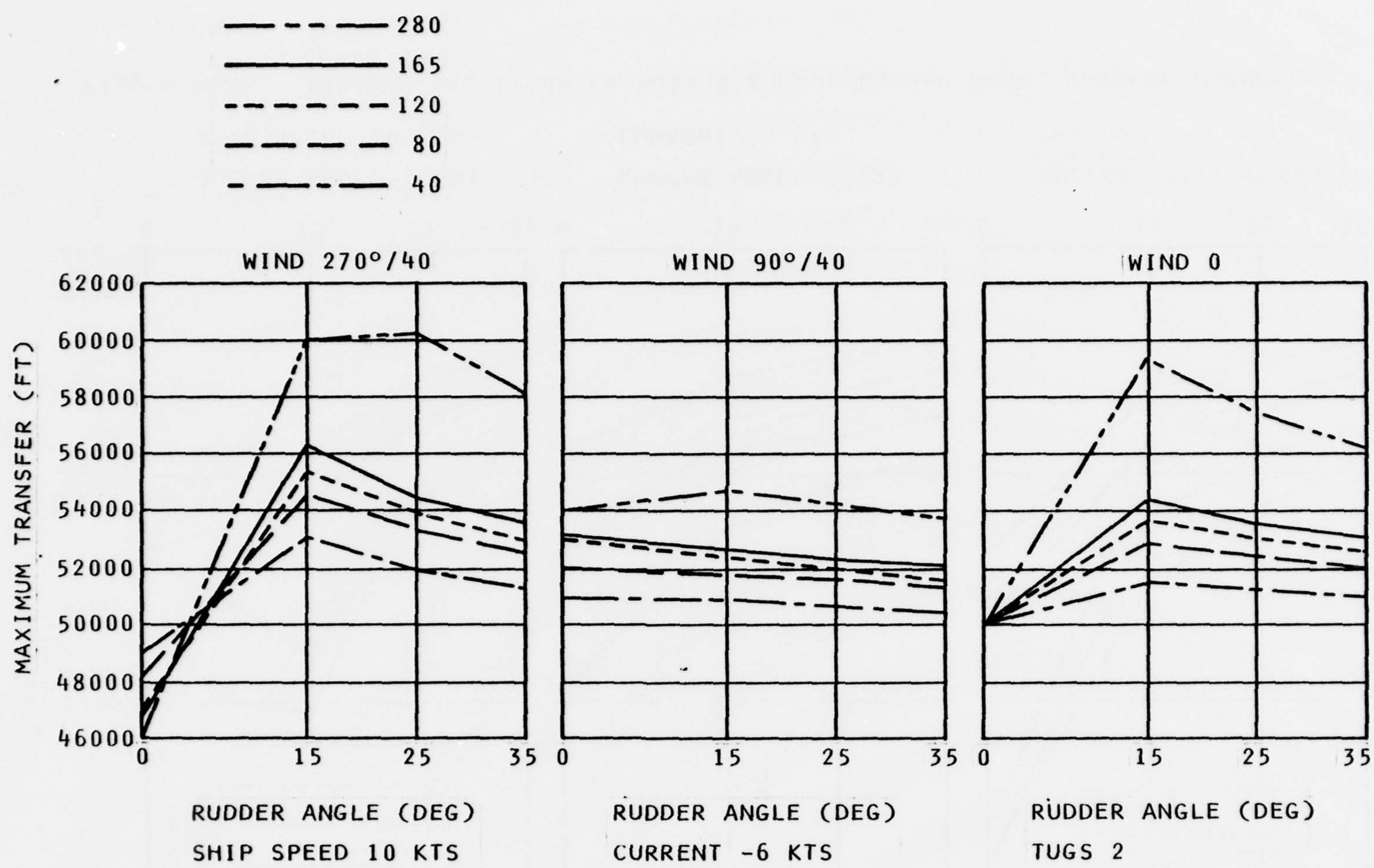

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 4)

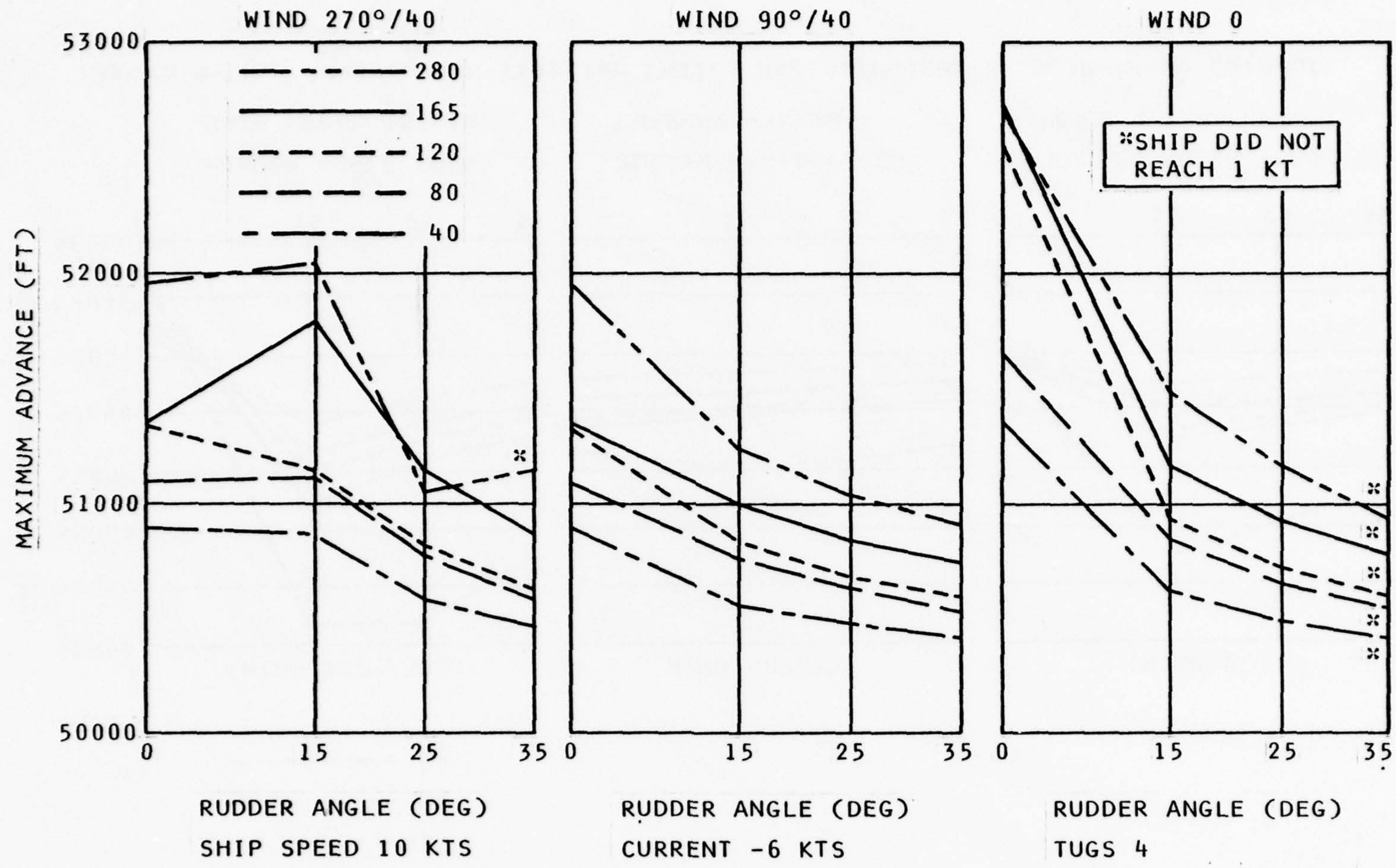

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 5)

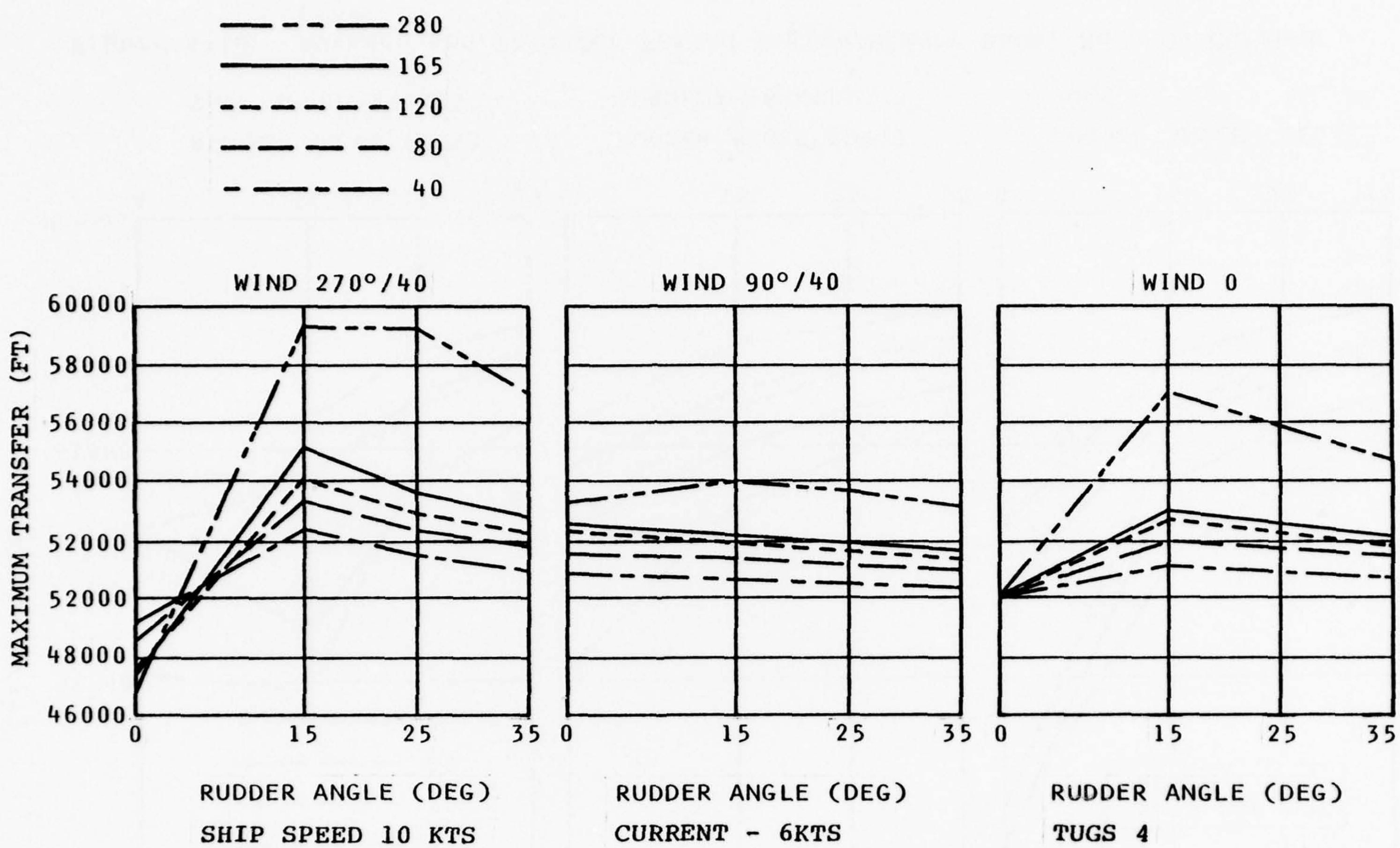

Figure 4-19. Advance and Transfer Failed Engine/Rudder Runs, Head-On Current (Part 6)

4. Except for 0^{o} rudder, as the values for failed rudder increase from 15^{o} to 35^{o}, advance and transfer values decrease.
5. The failed rudder magnitude which generally produces the greatest advance and transfer values lies approximately between 0^{o} and 15^{o}.
6. Except for 0^{o} rudder, the advance and transfer values decrease as the wind goes from 270^{o}/40 to 0 to 090^{o}/40.

4.3.2.2 Zero Current and 8-, 6- and 4-knot Ship Speed

A glance at Figure 4-20 indicates the general form of ground tracks taken by all ships in this series of runs. With 0^{o} rudder and a west wind, the ships transfer to the left. In most other cases (east wind or right rudder), the ships transfer to the right.

With regard to all ships and all speeds for zero current, the following general observations can be made (see Figure 4-21).

1. The variation of transfer and advance is more complex in this water current condition (0 kt) than in the previous one (-6 kts.).
2. For a ship speed of 8 knots:
   a) at zero-wind:
      i) advance decreases as rudder angles increase
      ii) maximum transfer occurs approximately at 15^{o} rudder.
   b) at 090^{o}/40 wind:
      i) advance decreases as rudder angles increase
      ii) transfer is approximately independent (constant) of rudder angle.
   c) at 270^{o}/40:
      i) maximum advance occurs approximately at a 15^{o} rudder.
      ii) variation of transfer is complex.

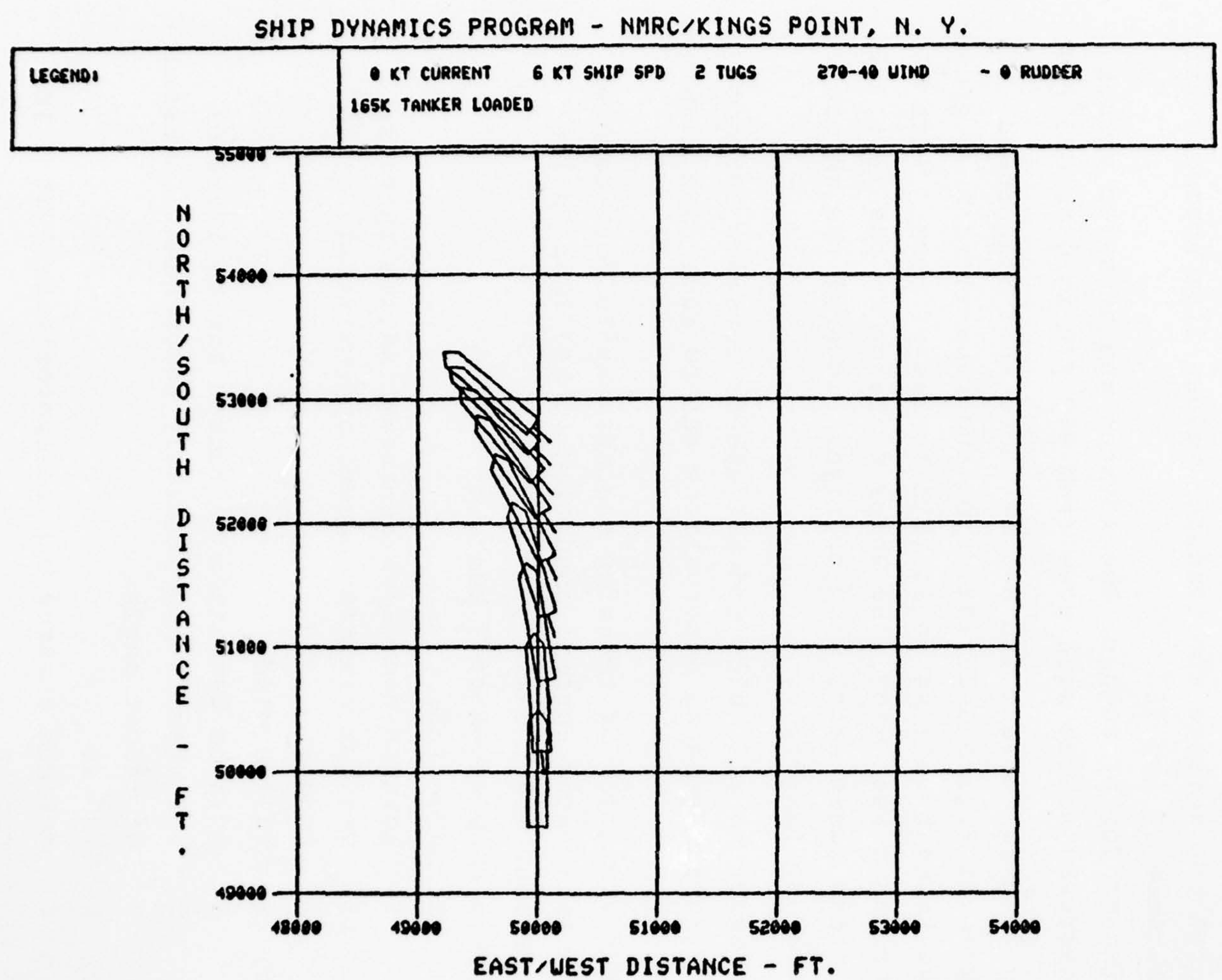

Figure 4-20. Typical Ground Track, Failed Engine/Rudder Run, 0 kt Current (Part 1, 0° Rudder, West Wind)

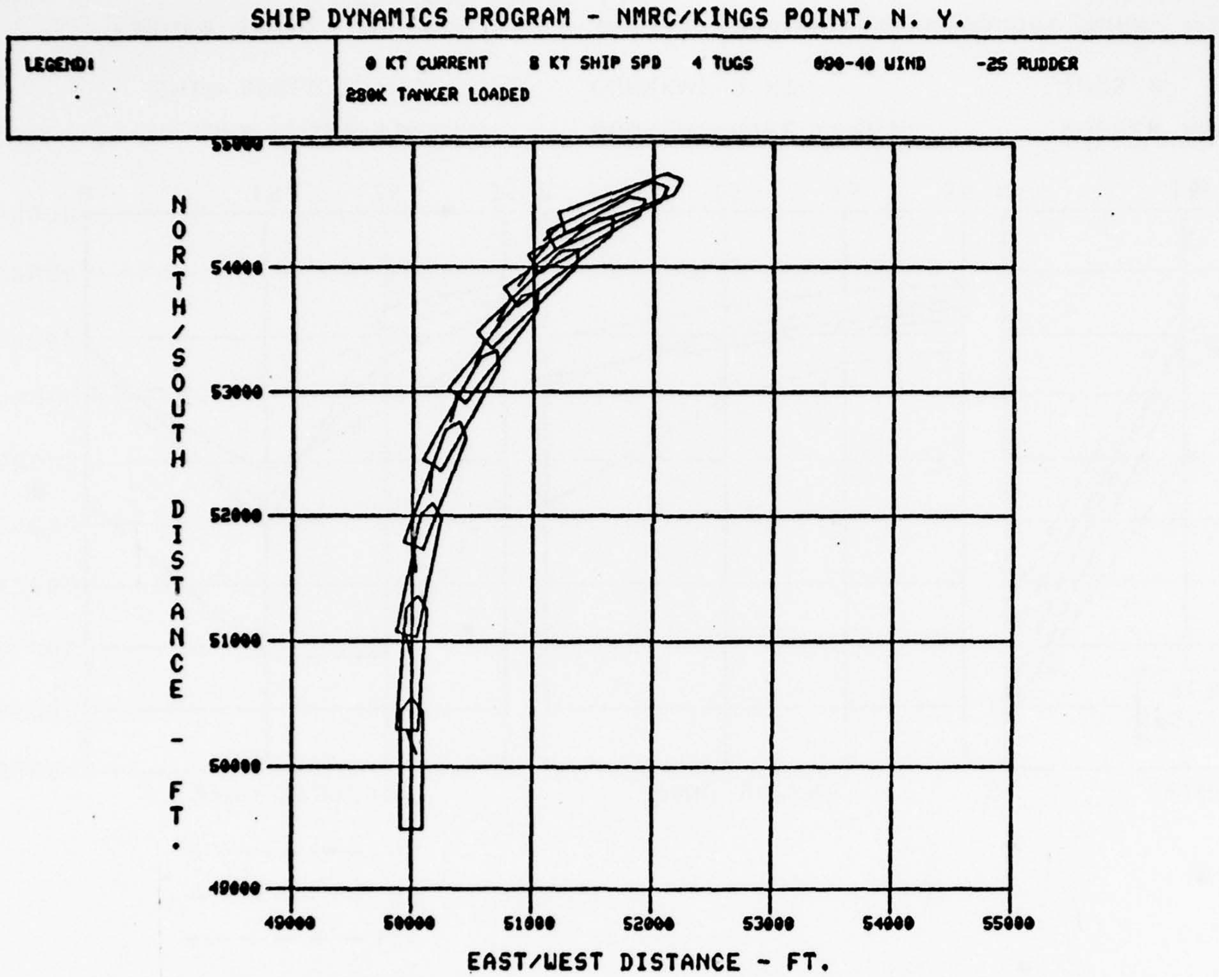

Figure 4-20. Typical Ground Track, Failed Engine/Rudder Run, 0 kt Current (Part 2, 25° Rudder, East Wind)

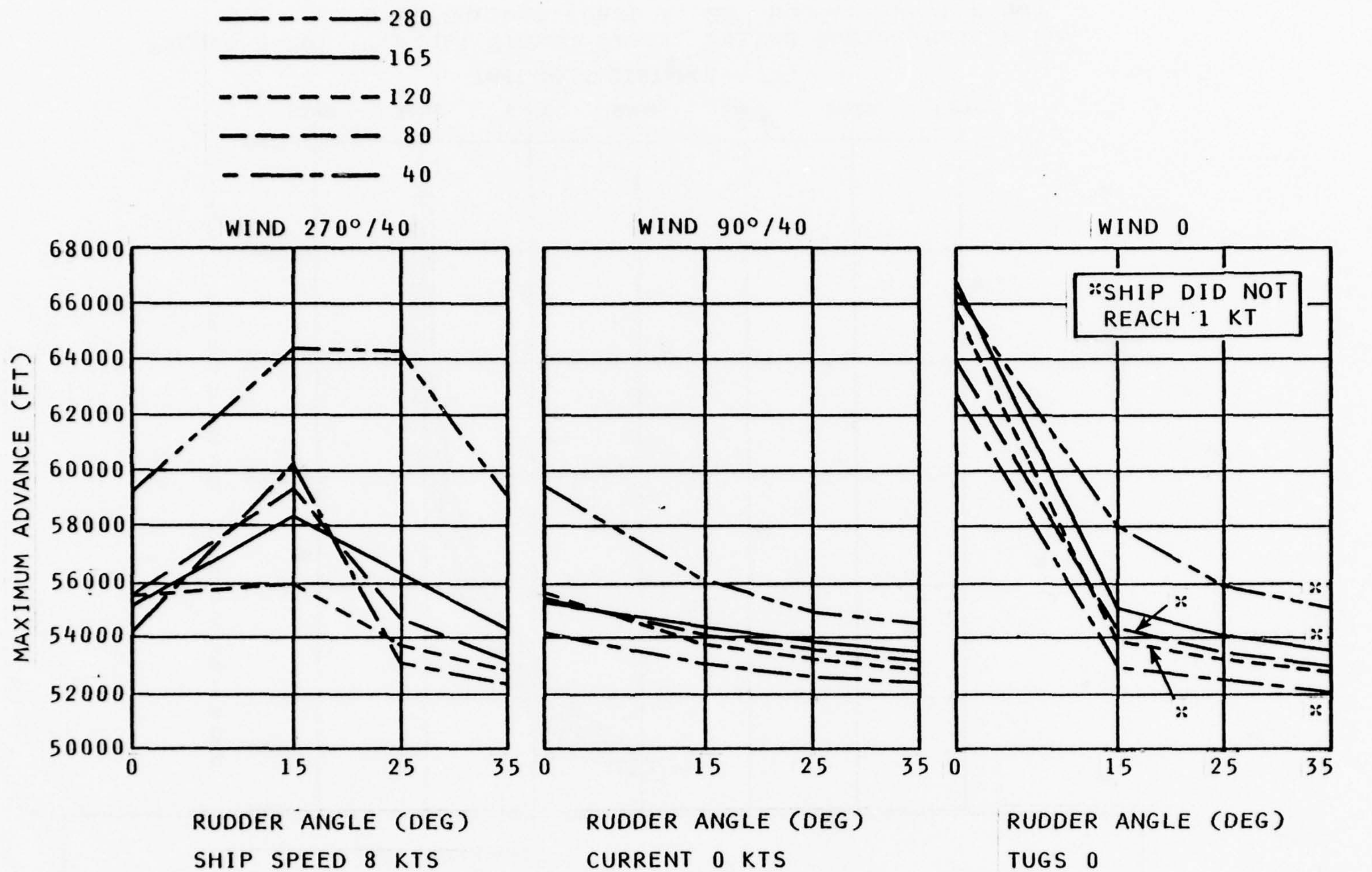

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 1)

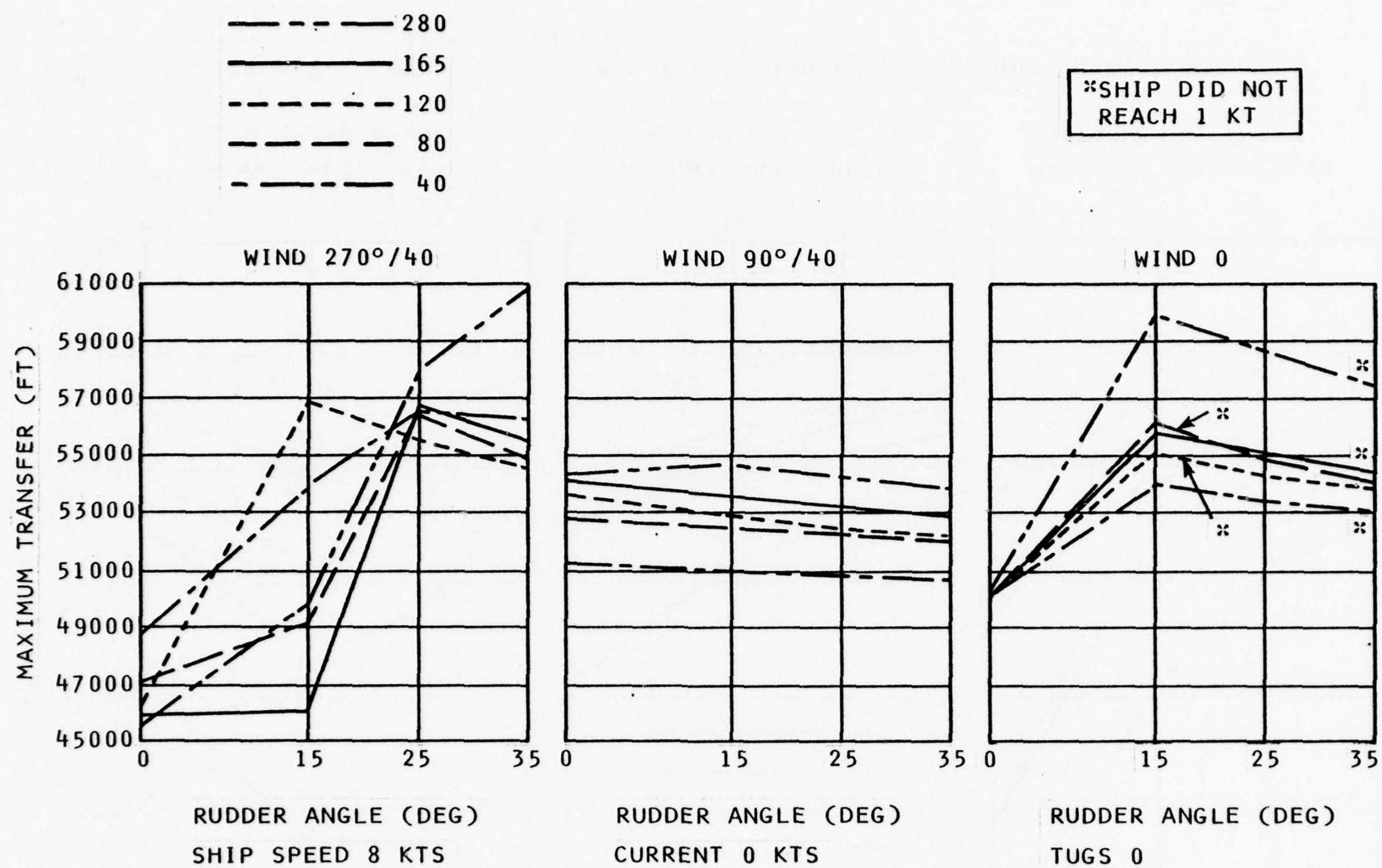

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 2)

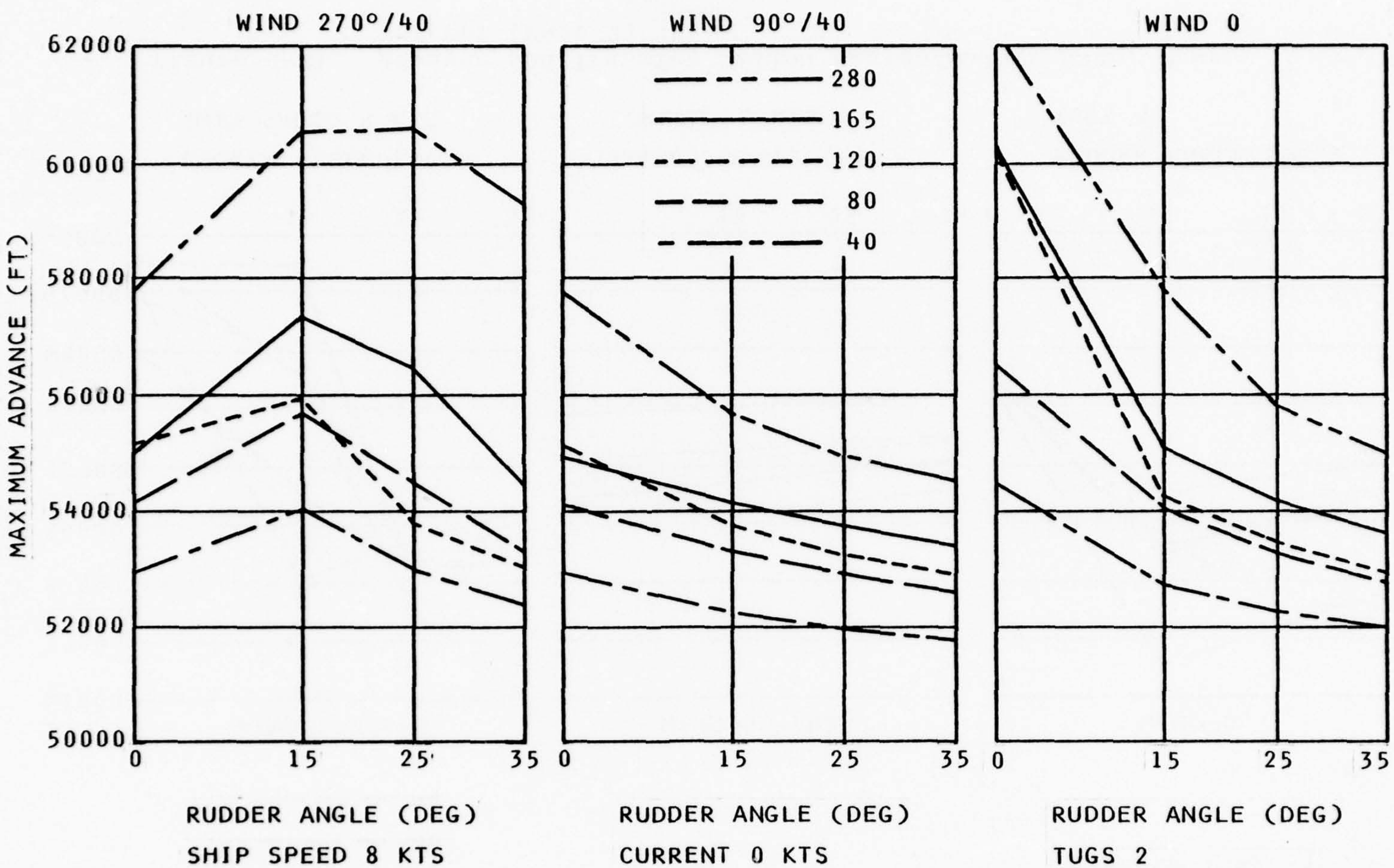

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 3)

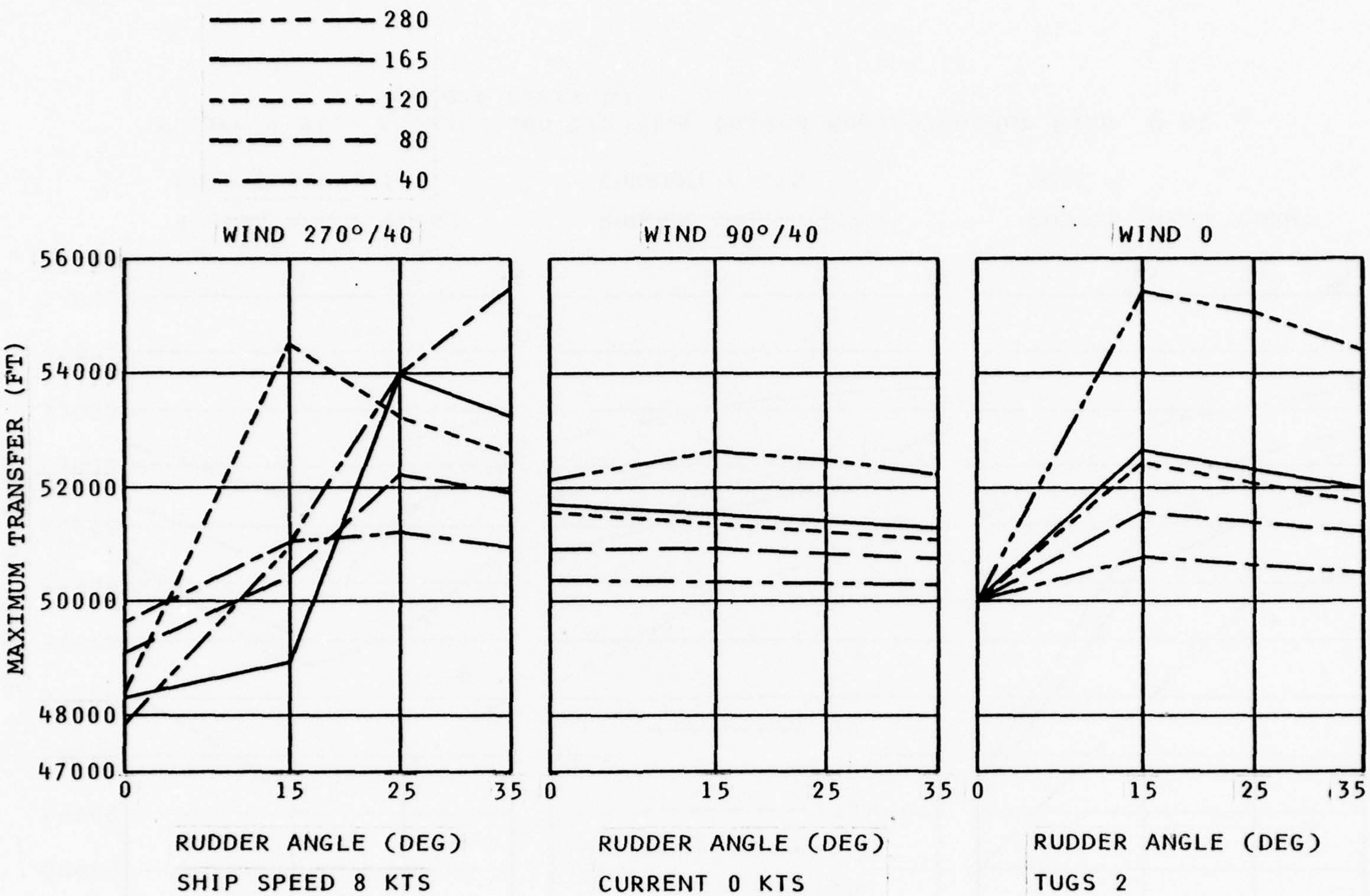

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 4)

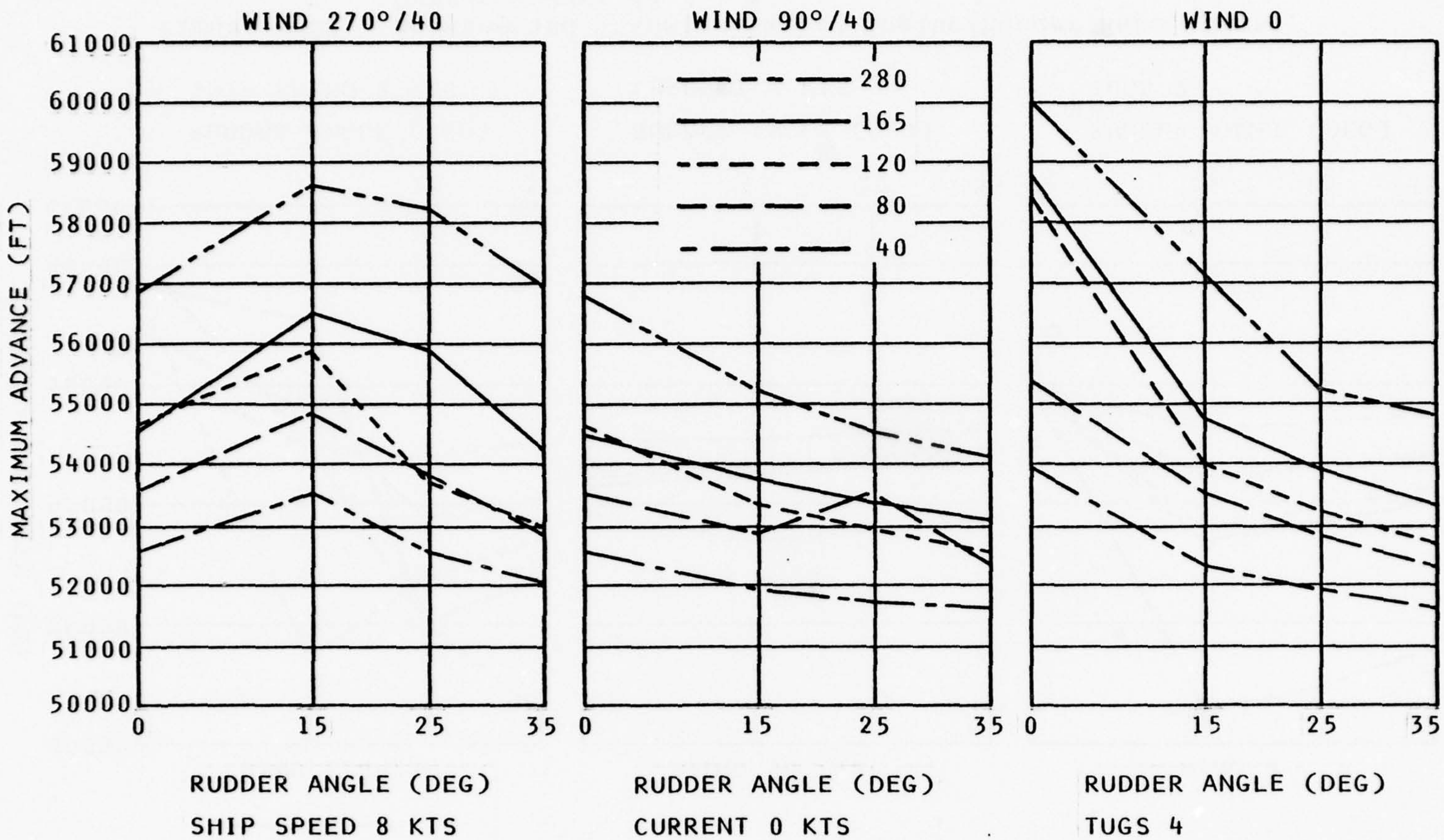

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 5)

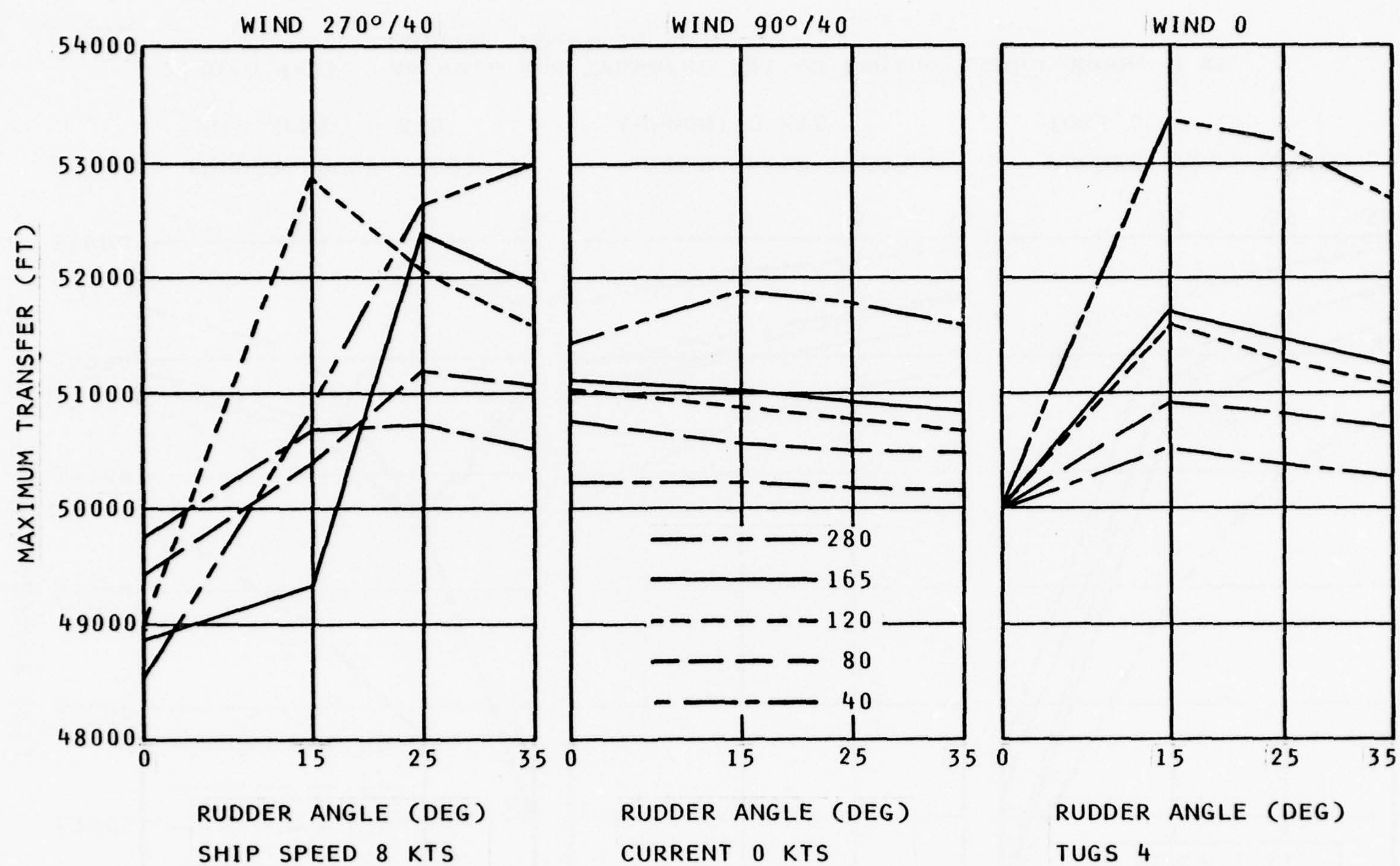

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 6)

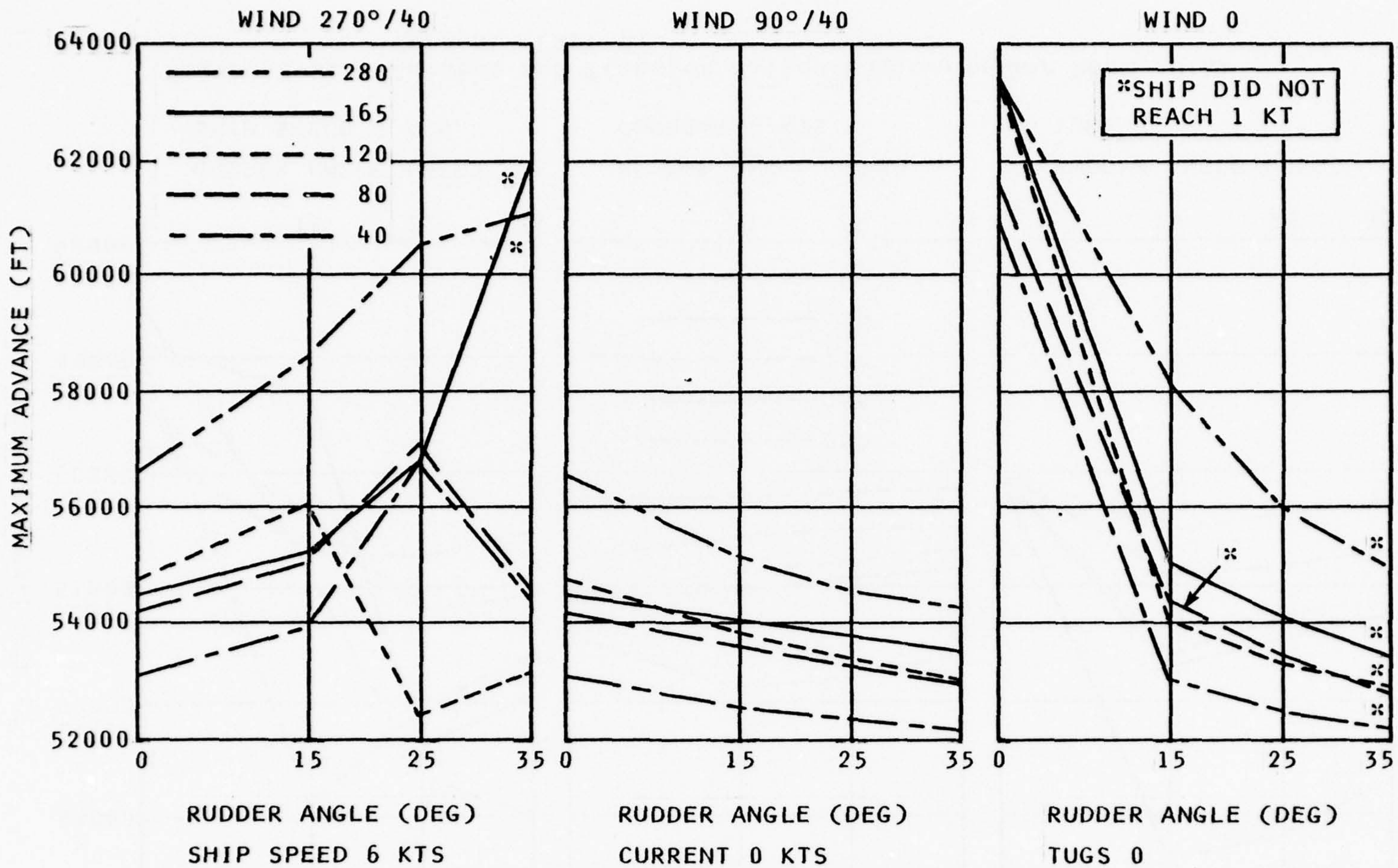

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 7)

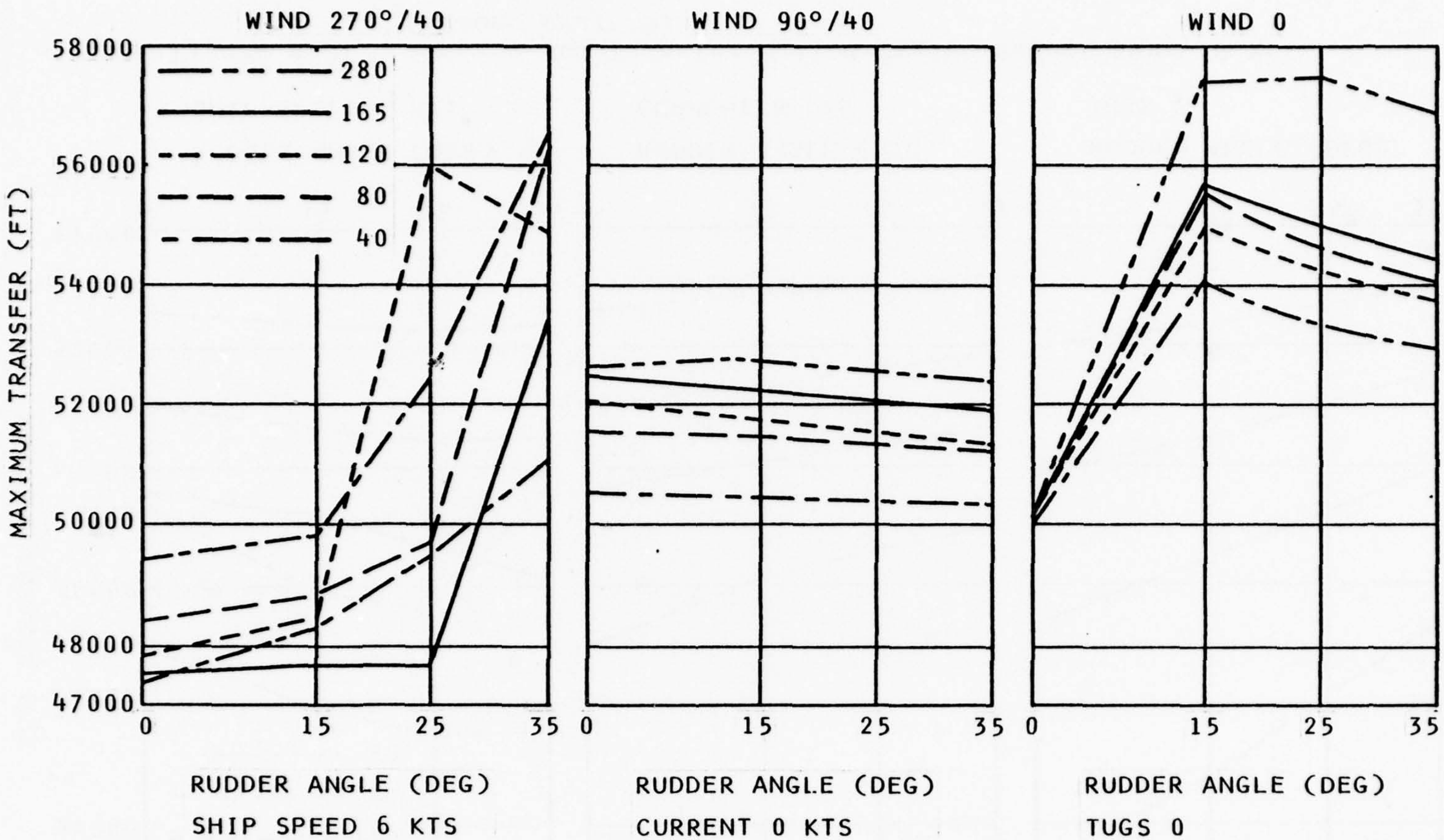

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 8)

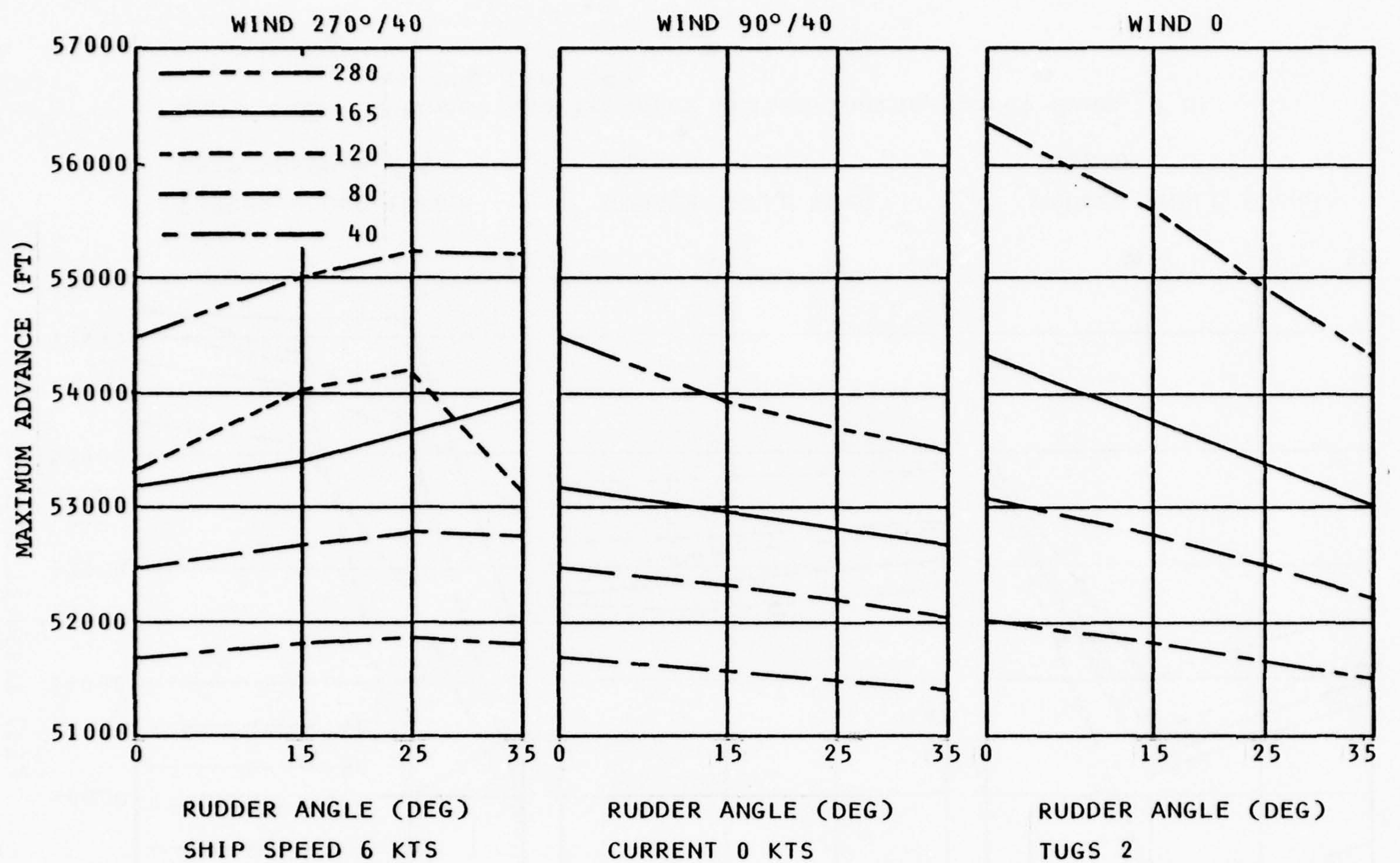

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 9)

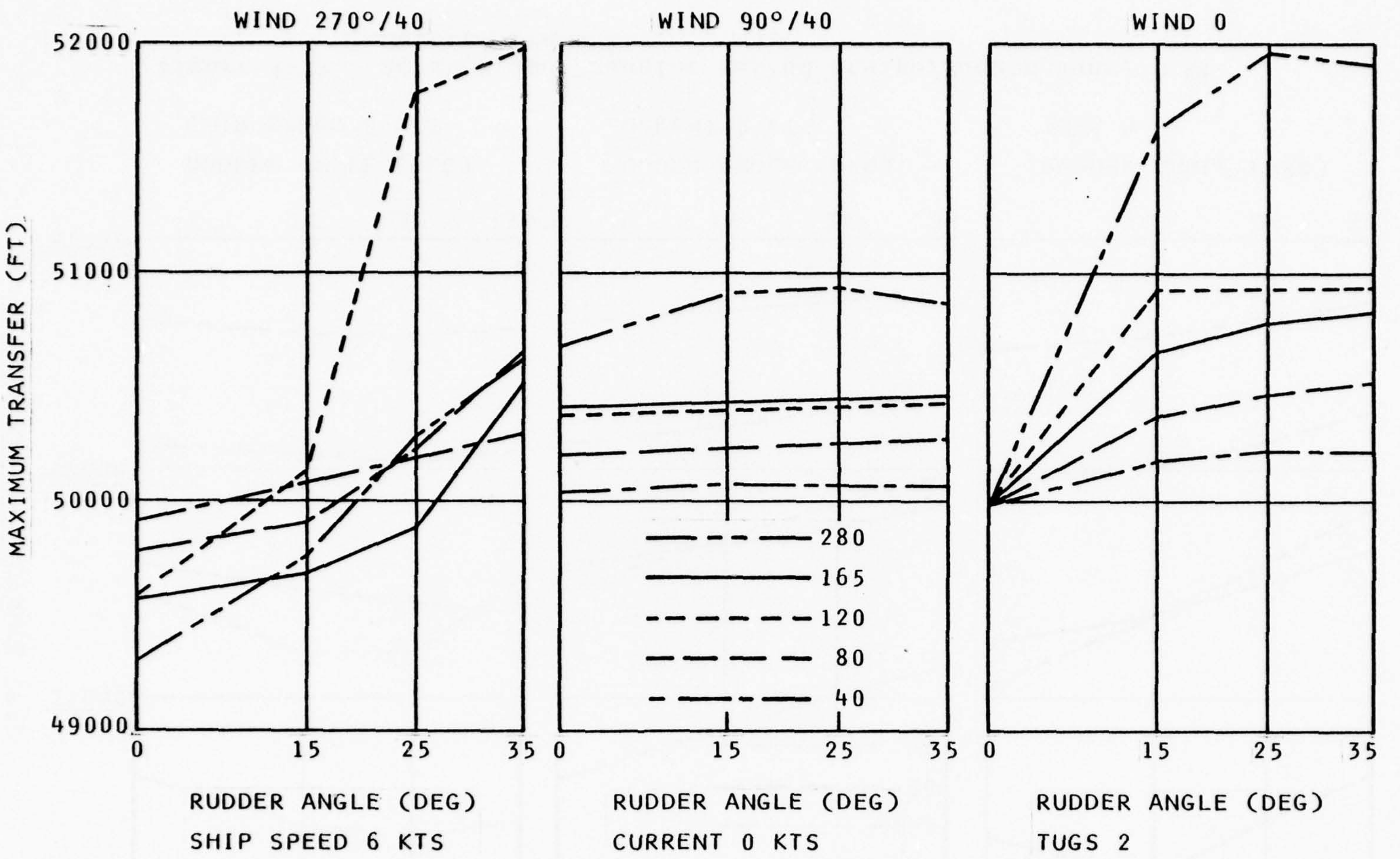

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 10)

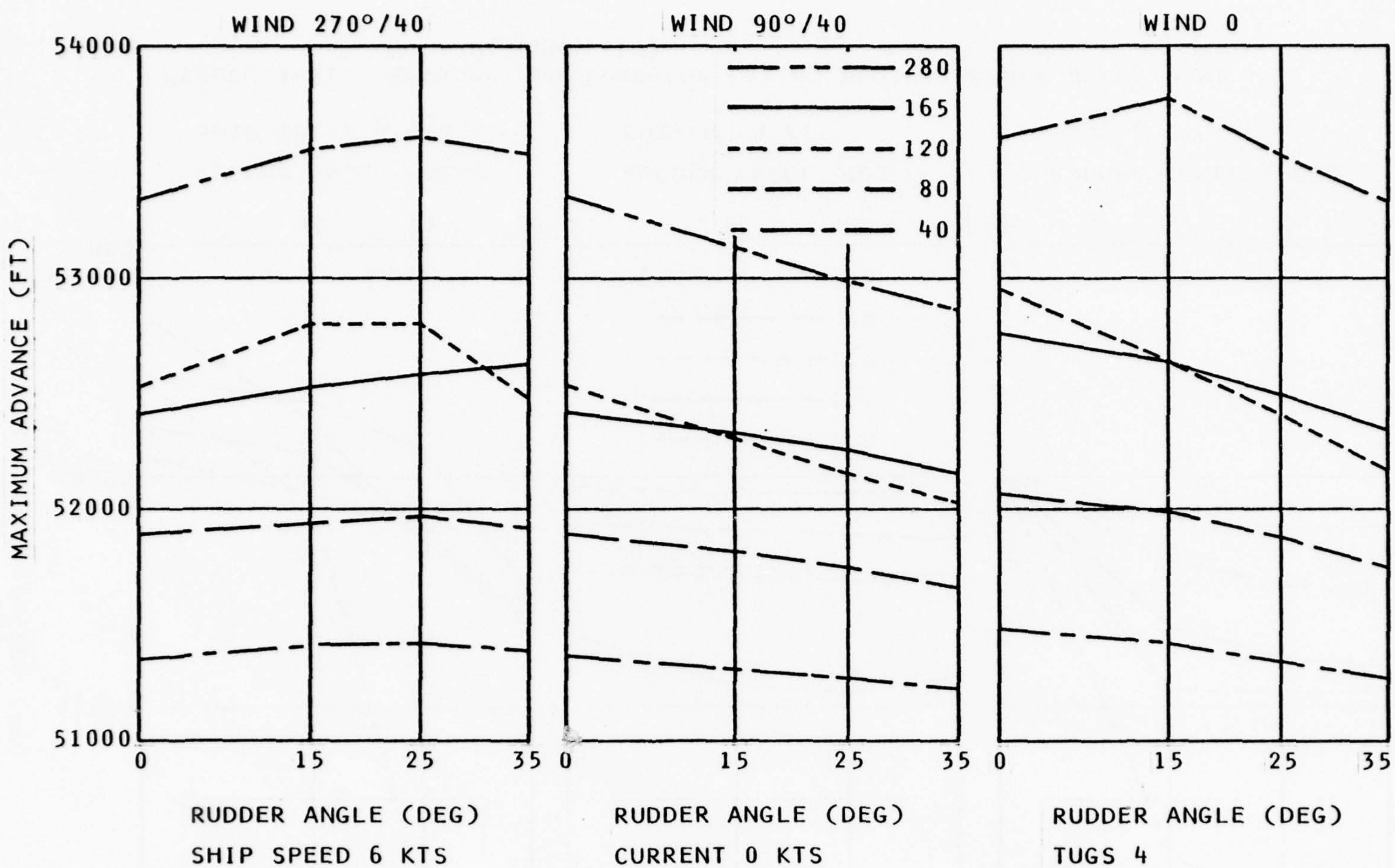

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 11)

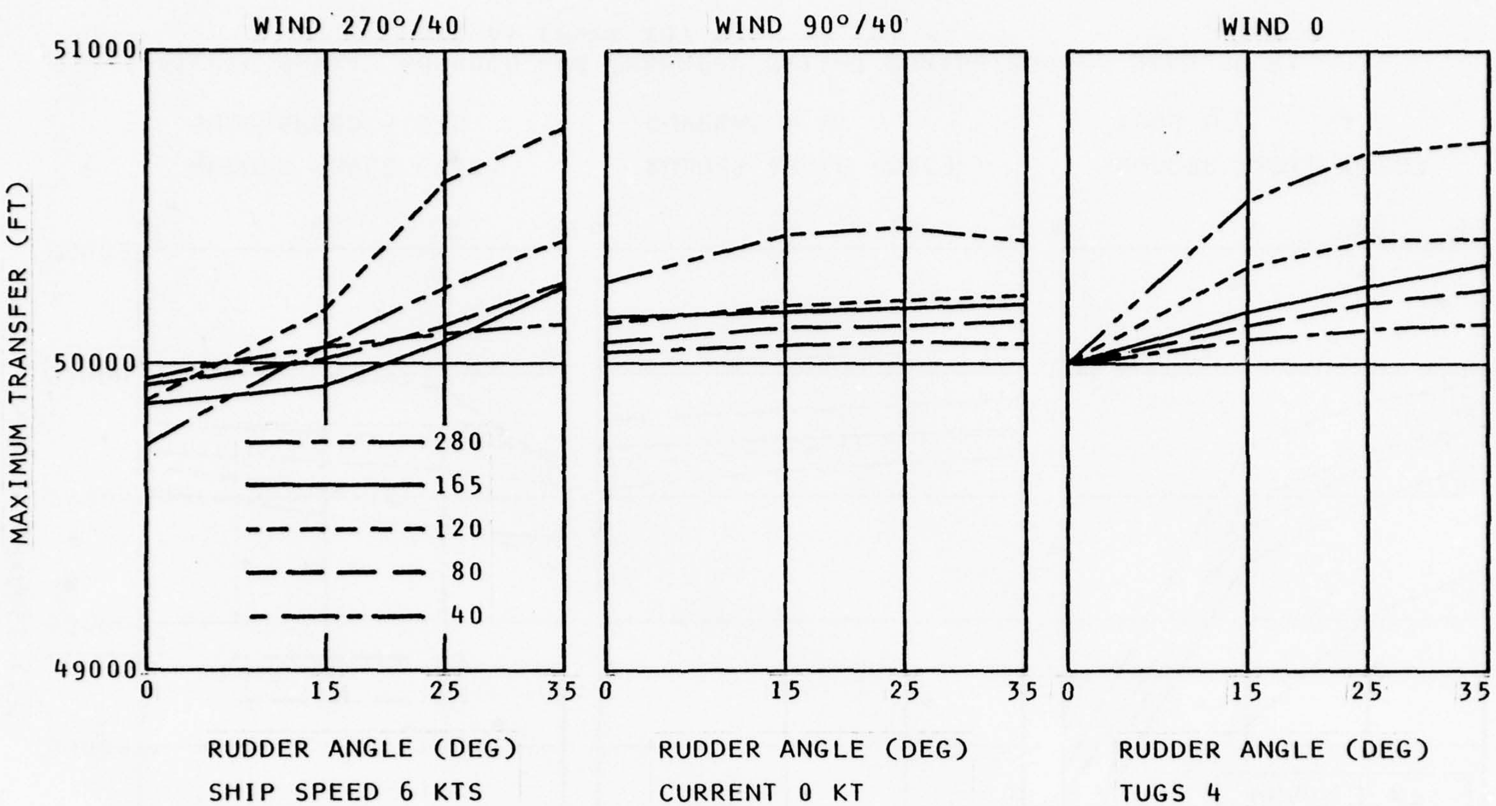

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 12)

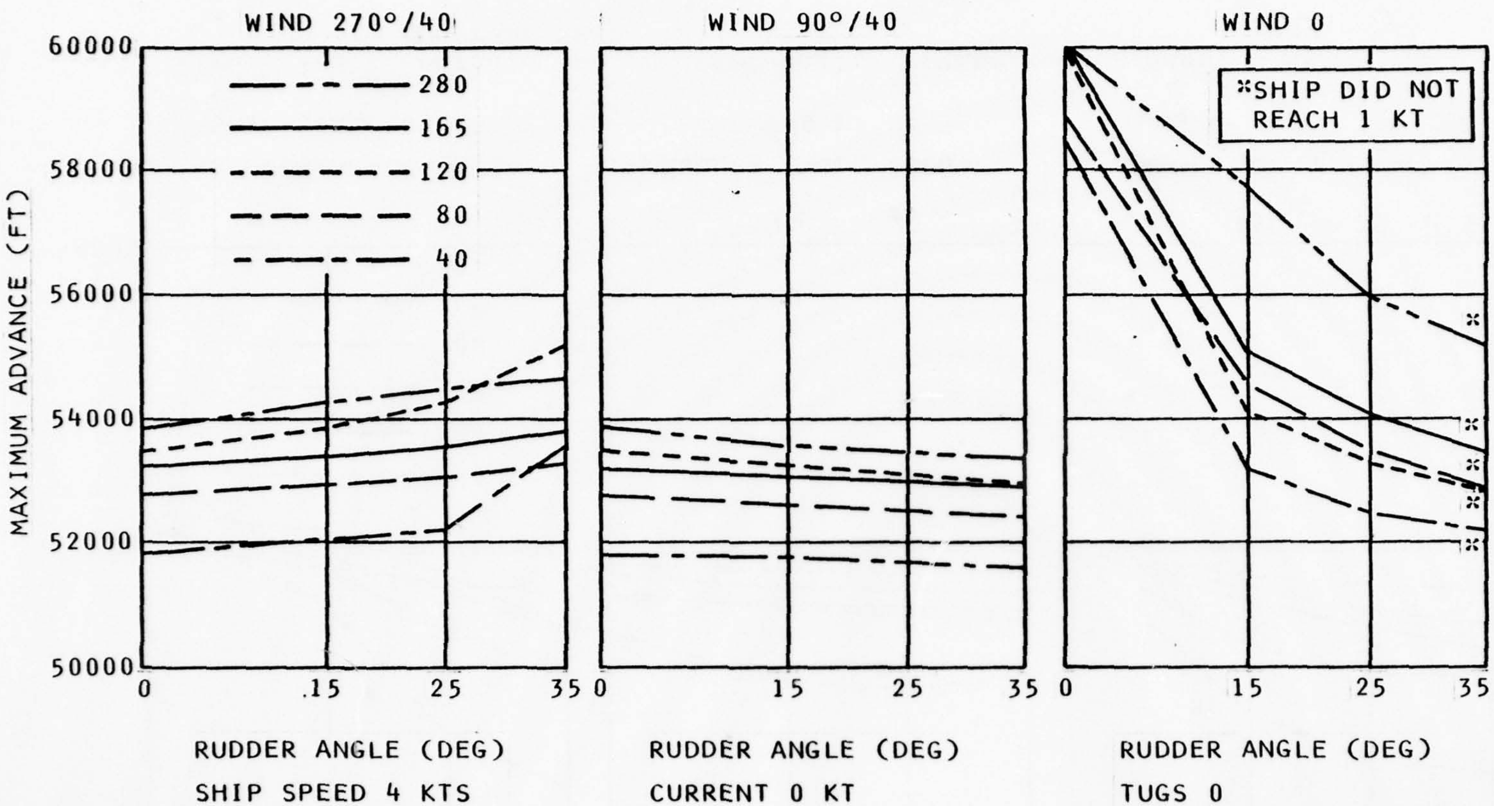

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 13)

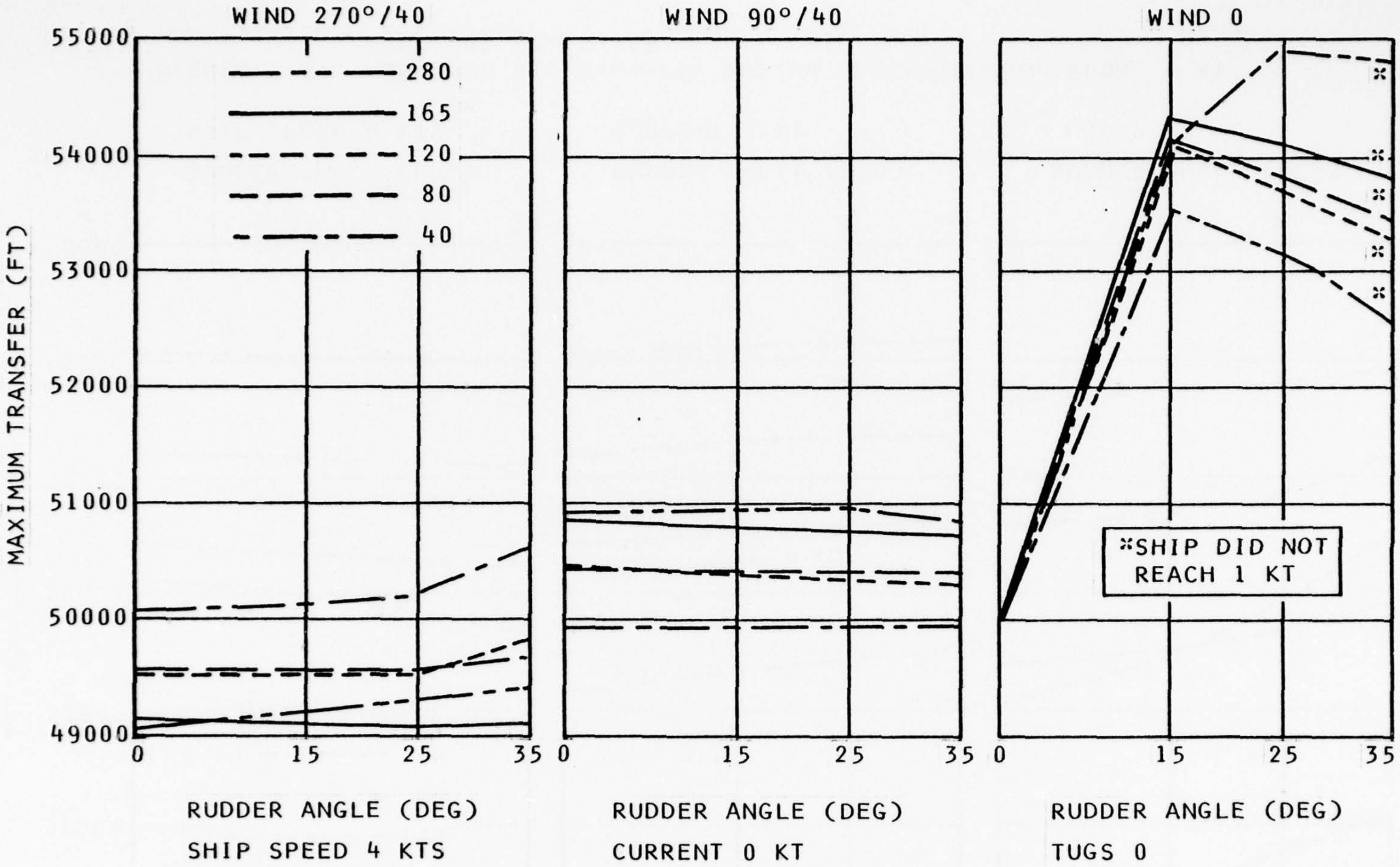

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 14)

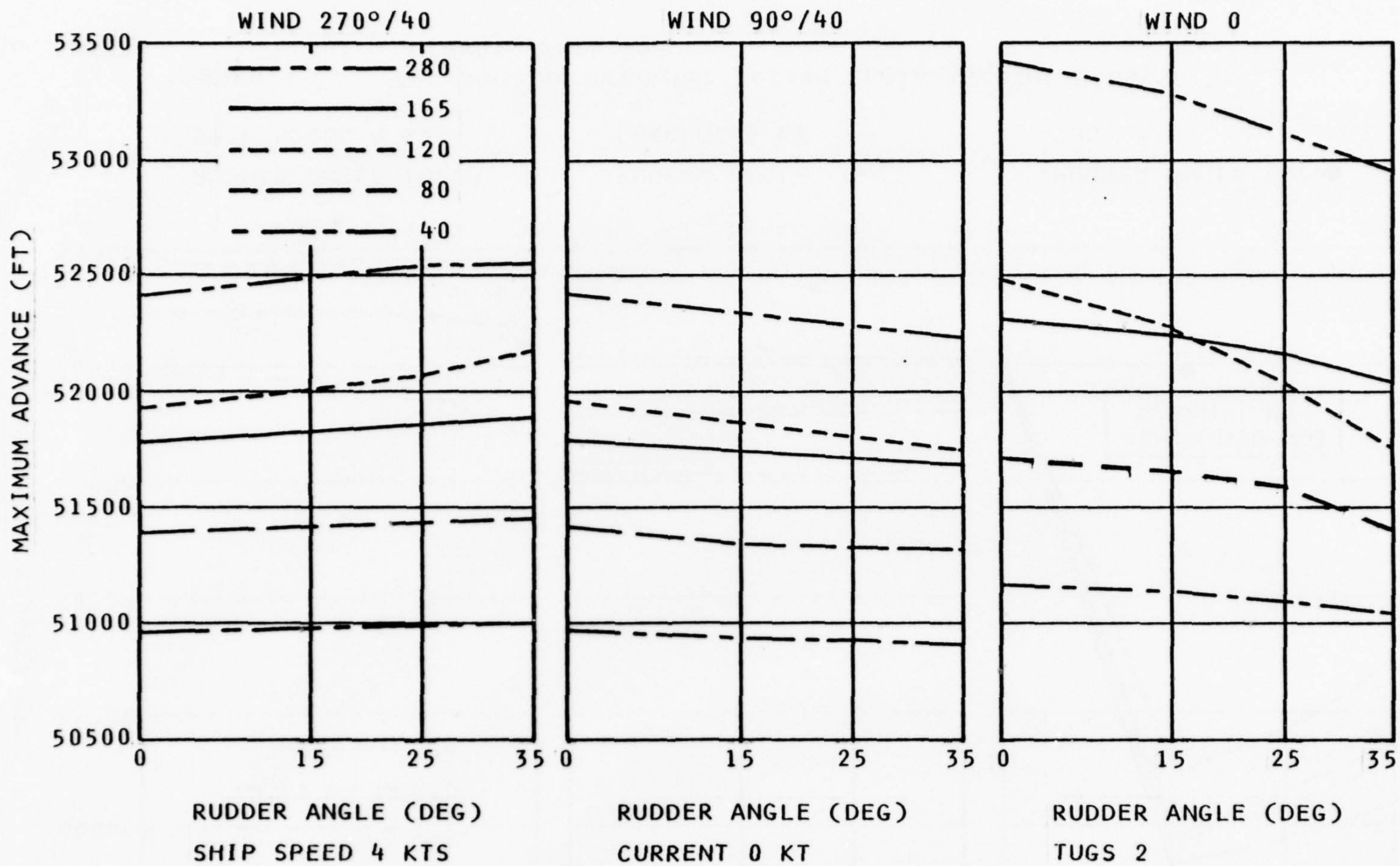

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 15)

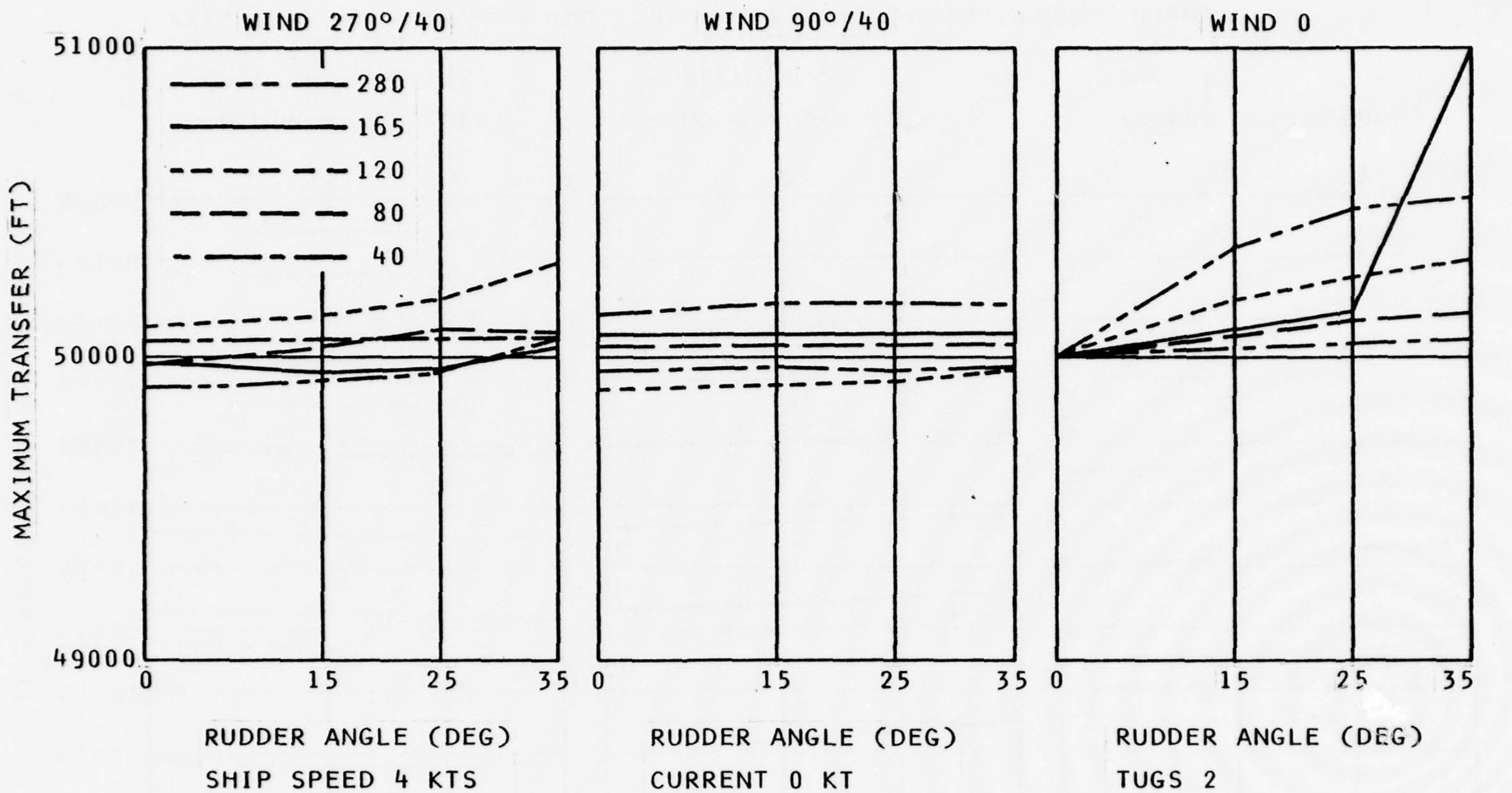

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 16)

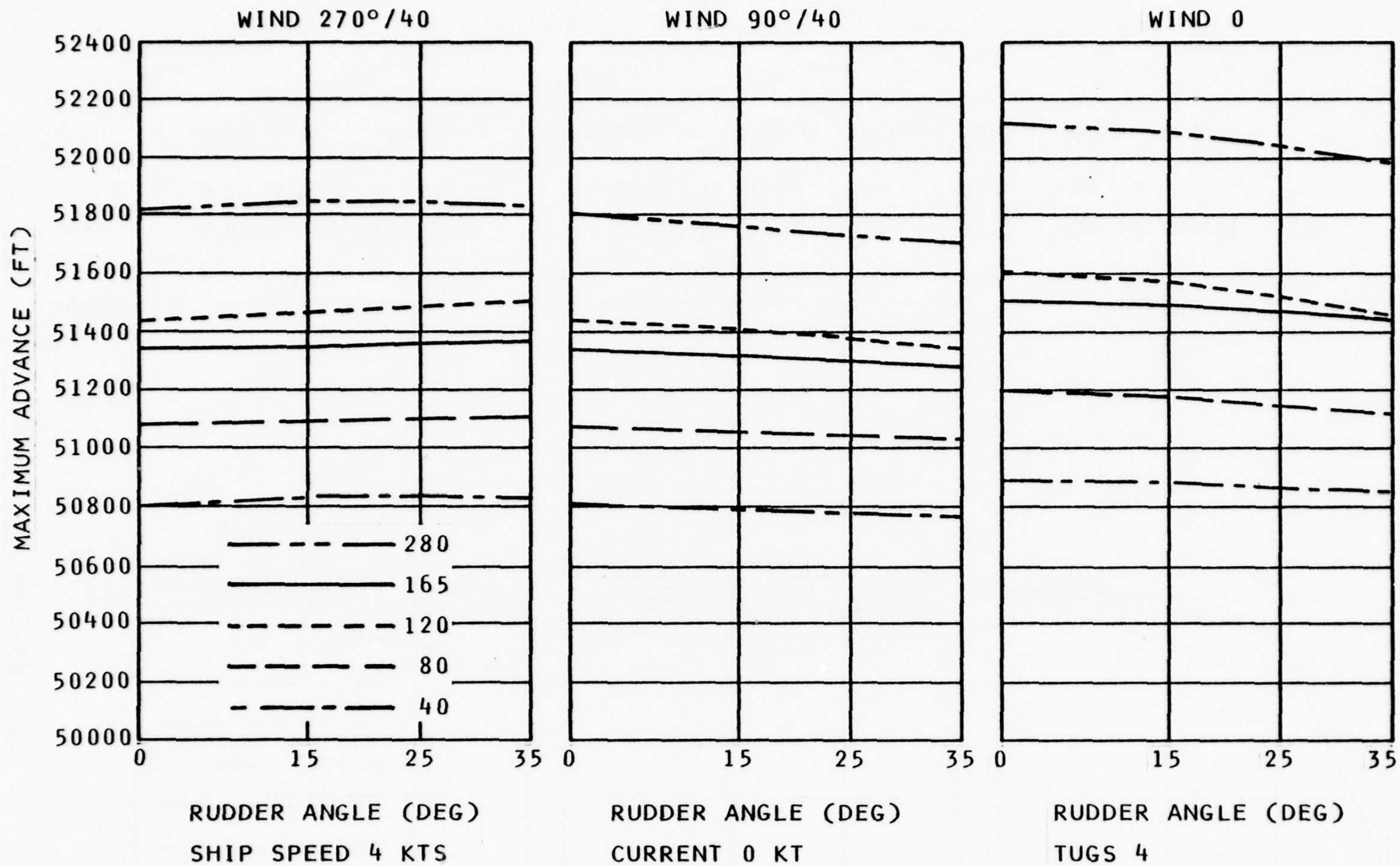

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 17)

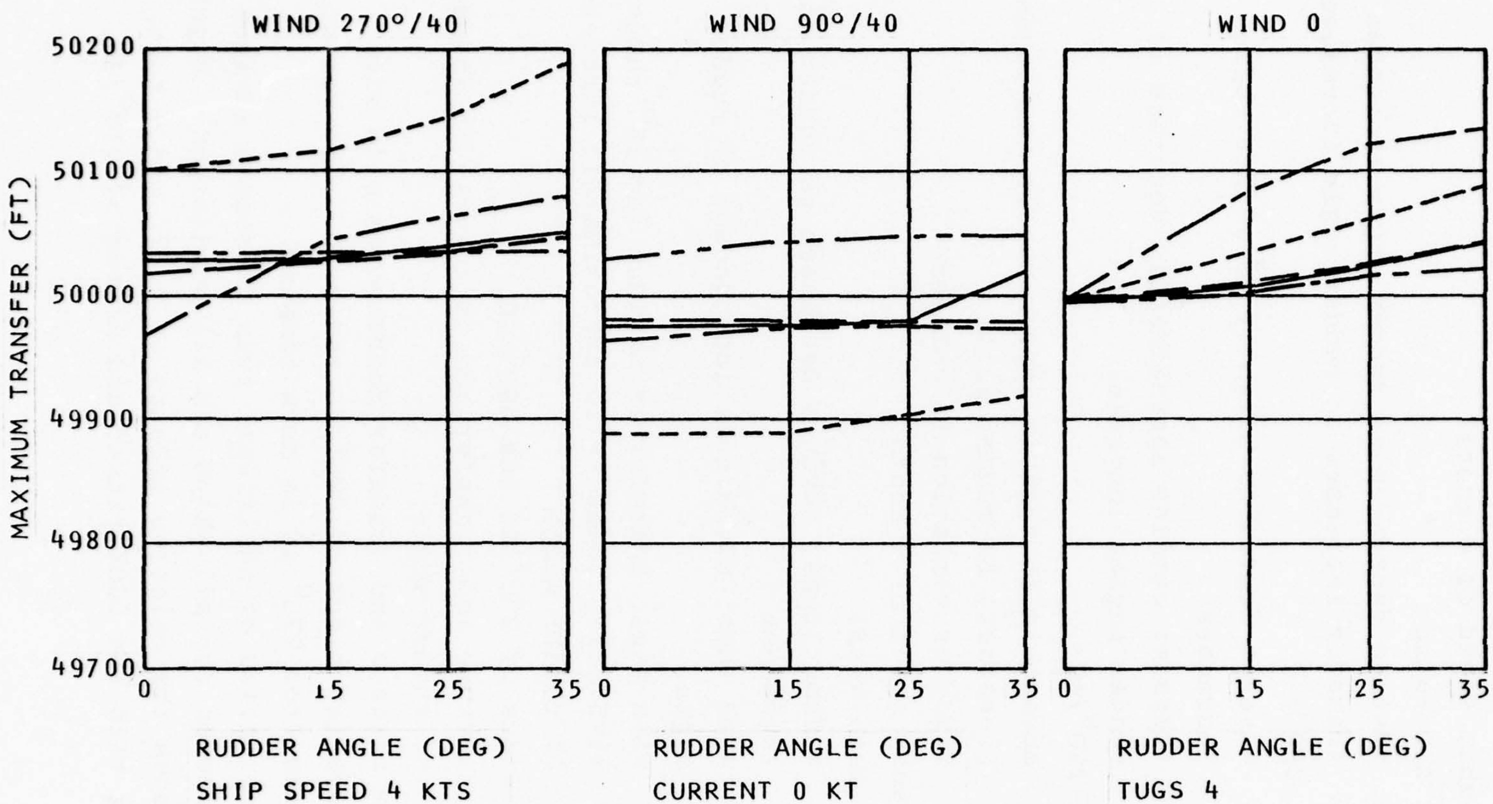

Figure 4-21. Advance and Transfer Failed Engine/Rudder Runs, 0 kt Current (Part 18)

3. For a ship speed of 6 knots:
   a) at zero-wind:
      i) advance decreases as rudder angle increases
      ii) transfer increases as rudder angle increases.
   b) at $090^{\circ}/40$:
      i) advance decreases slightly as rudder angle increases
      ii) transfer remains approximately constant as rudder angles increase.
   c) at $270^{\circ}/40$:
      i) advance with tugs is approximately independent (constant) of rudder angle
      ii) transfer variation is complex.
4. For a ship speed of 4 knots:
   a) at zero-wind:
      i) without tugs, advance decreases as rudder angle increases
      ii) with tugs, advance is independent of rudder angle
      iii) with tugs, transfer is maximum for 15° rudder
      iv) with tugs, transfer is approximately independent of rudder angle
   b) at winds of $270^{\circ}/40$ and $090^{\circ}/40$:
      i) advance and transfer are relatively independent of rudder angle.
5. Maximum advance and transfer decrease as ship size decreases for winds of $090^{\circ}/40$ and zero. The variation for winds from $270^{\circ}/40$ is more complex.
6. The application of additional tugs decreases advance and transfer for all ships and all conditions. Figure 4-22 shows the relative effects of 0, 2, and 4 tugs backing with the 280K tanker and a wind of $270^{\circ}/40$.

7. As the initial speed of ships decreases, the advance and transfer values also decrease. Figure 4-23 shows the effect of changes in initial ship speed from 4 to 8 knots upon the subsequent advance and transfer of the 280K tanker.

4.3.2.3 Following Current (+6 kts.) and 8-, 6-, and 4-knot Ship Speed

Inspection of Figures 4-24 and 4-25 reveals the general shape of the ground tracks traced out by the ships in this series of runs. In the presence of a west wind and with 0° rudder, the ship transfers to the left. In many, but not all, other cases, the ship goes to the right. The presence of the strong following current increases the advance in all cases.

Inspection of Figure 4-26 allows one to draw the following conclusions:

1. For a ship speed of 8 knots:
   - a) at zero-wind:
     - i) advance decreases as rudder increases
     - ii) transfer is a maximum for 15° rudder.
   - b) at $090^{\circ}/40$:
     - i) advance decreases as rudder increases
     - ii) transfer is approximately independent of rudder angle.
   - c) at $270^{\circ}/40$:
     - i) advance is a maximum for rudder of 15° to 25°
     - ii) variation of transfer is complex.
2. For a ship speed of 6 knots:
   - a) at zero-wind:
     - i) advance decreases as rudder angle increases
     - ii) without tugs, maximum transfer occurs at approximately 15° rudder
     - iii) with tugs, transfer increases as rudder angle increases.

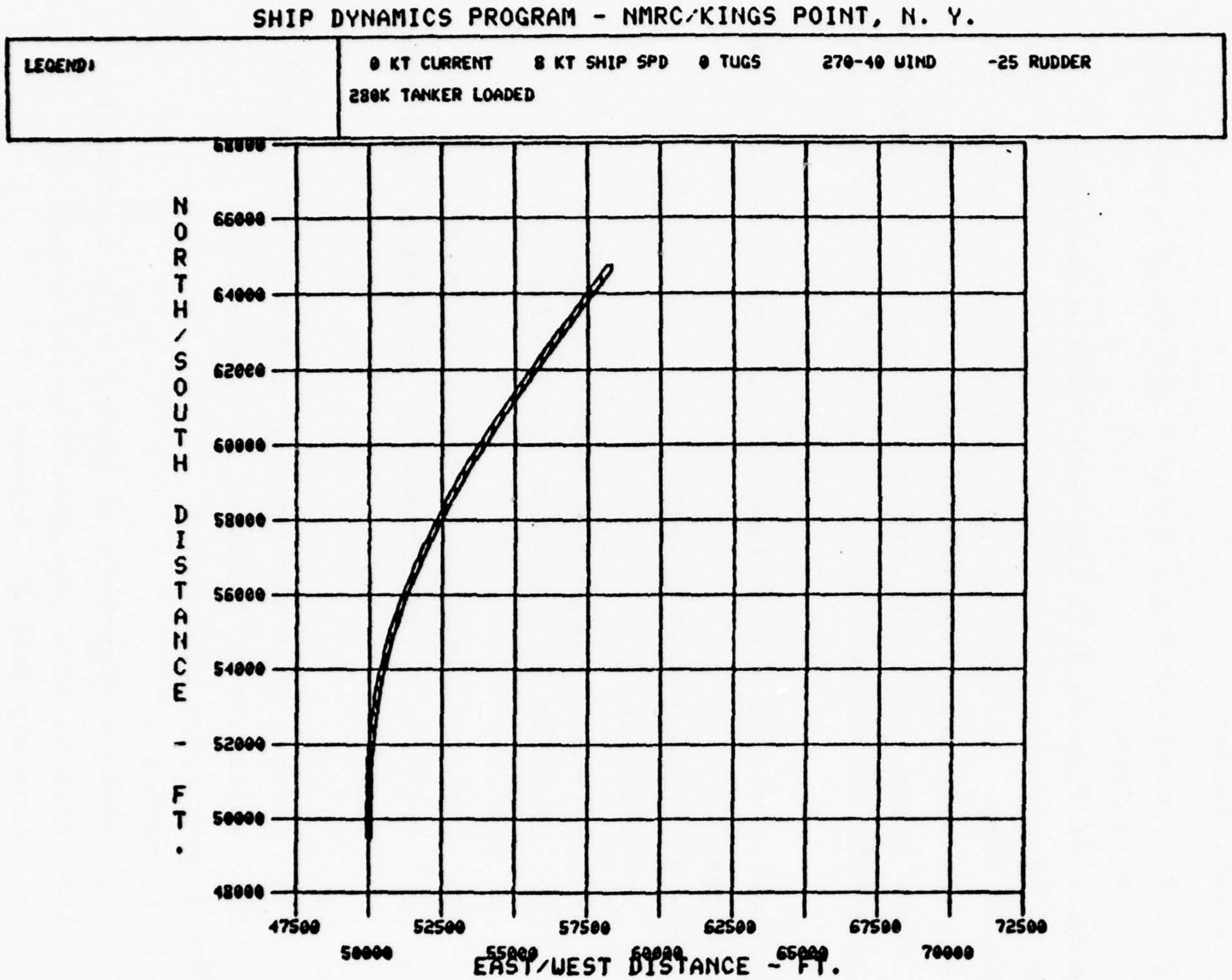

Figure 4-22. Relative Effect of Number of Tugs on Advance and Transfer (Part 1, 0 Tugs)

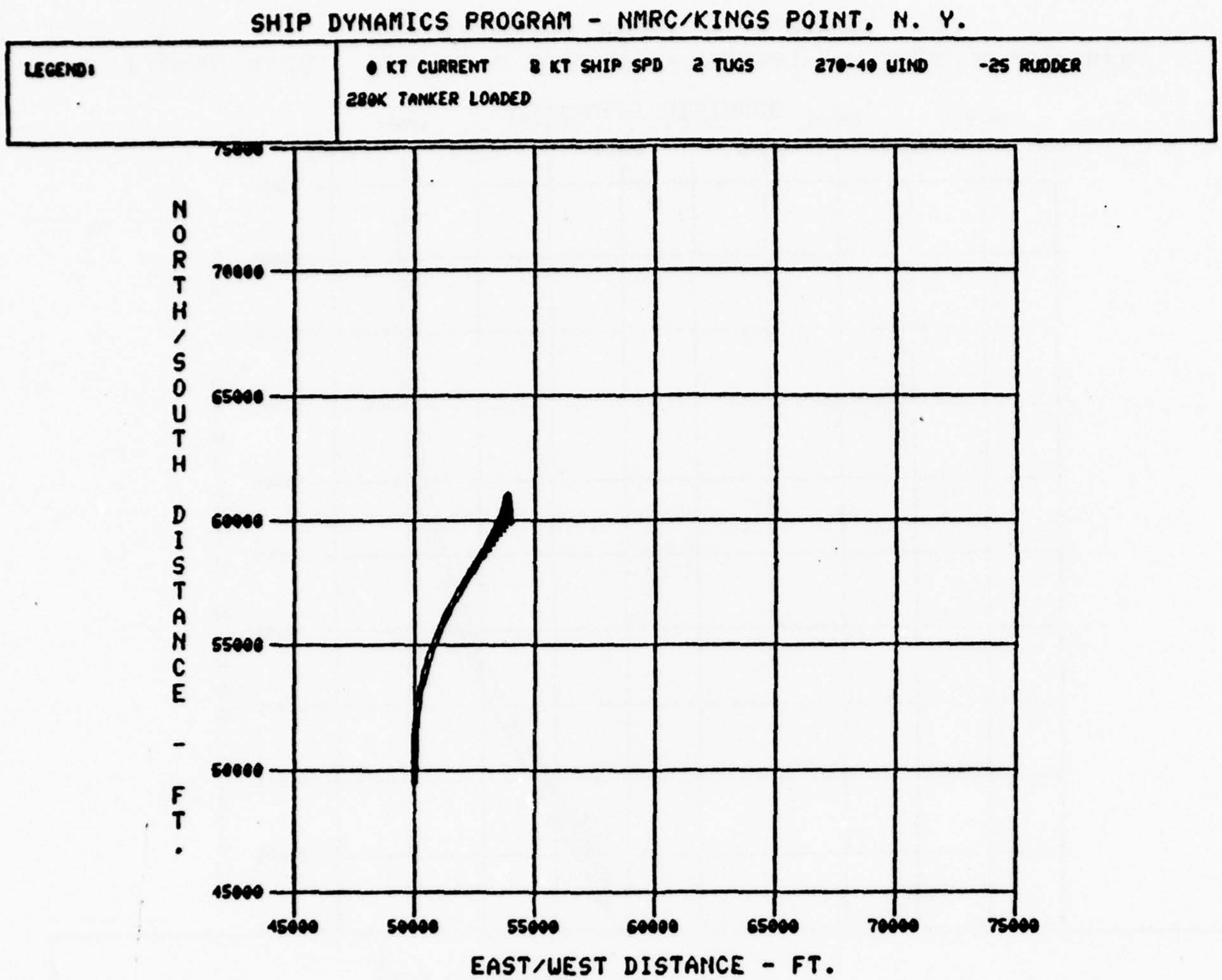

Figure 4-22. Relative Effect of Number of Tugs on Advance and Transfer (Part 2, 2 Tugs)

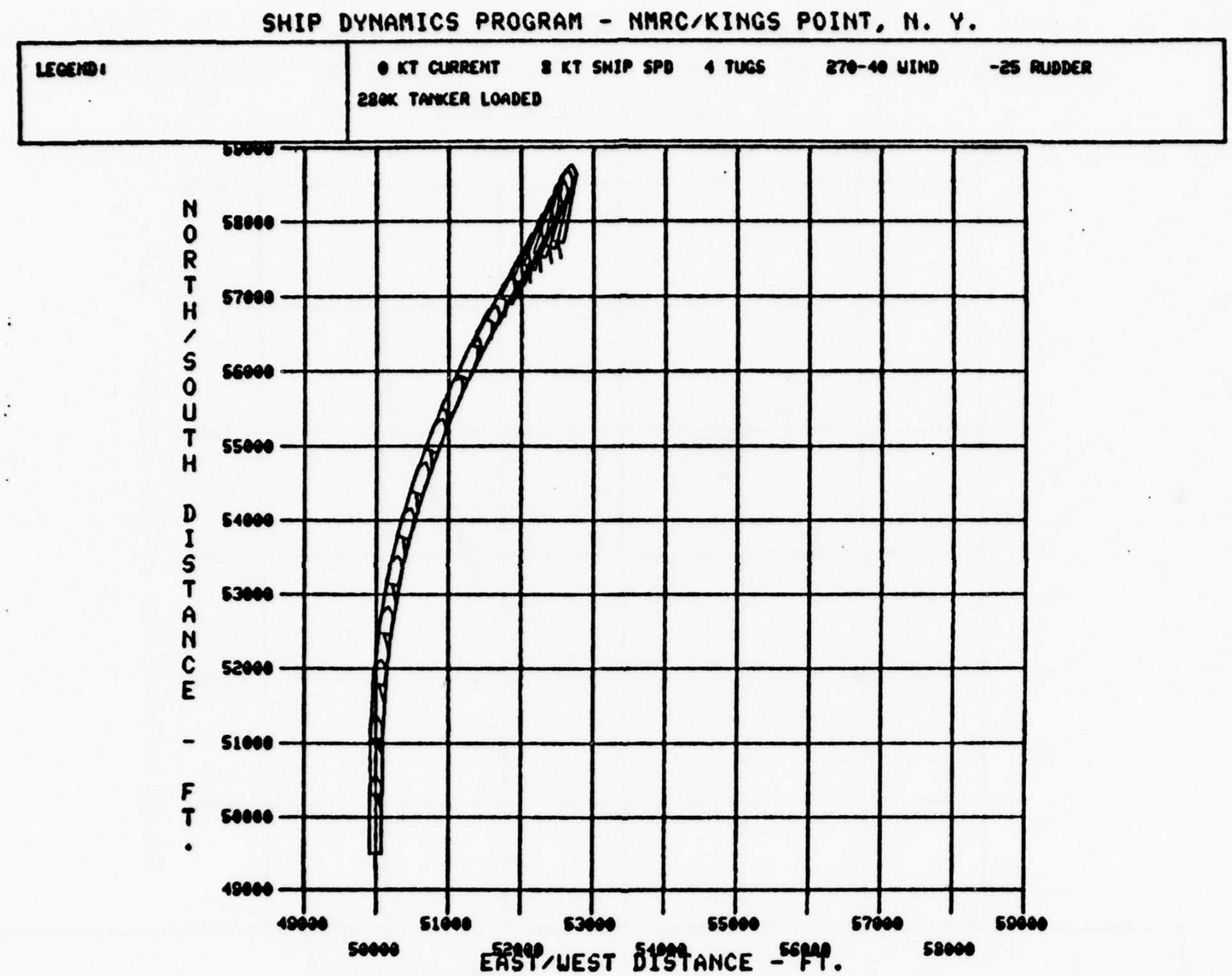

Figure 4-22. Relative Effect of Number of Tugs on Advance and Transfer (Part 3, 4 Tugs)

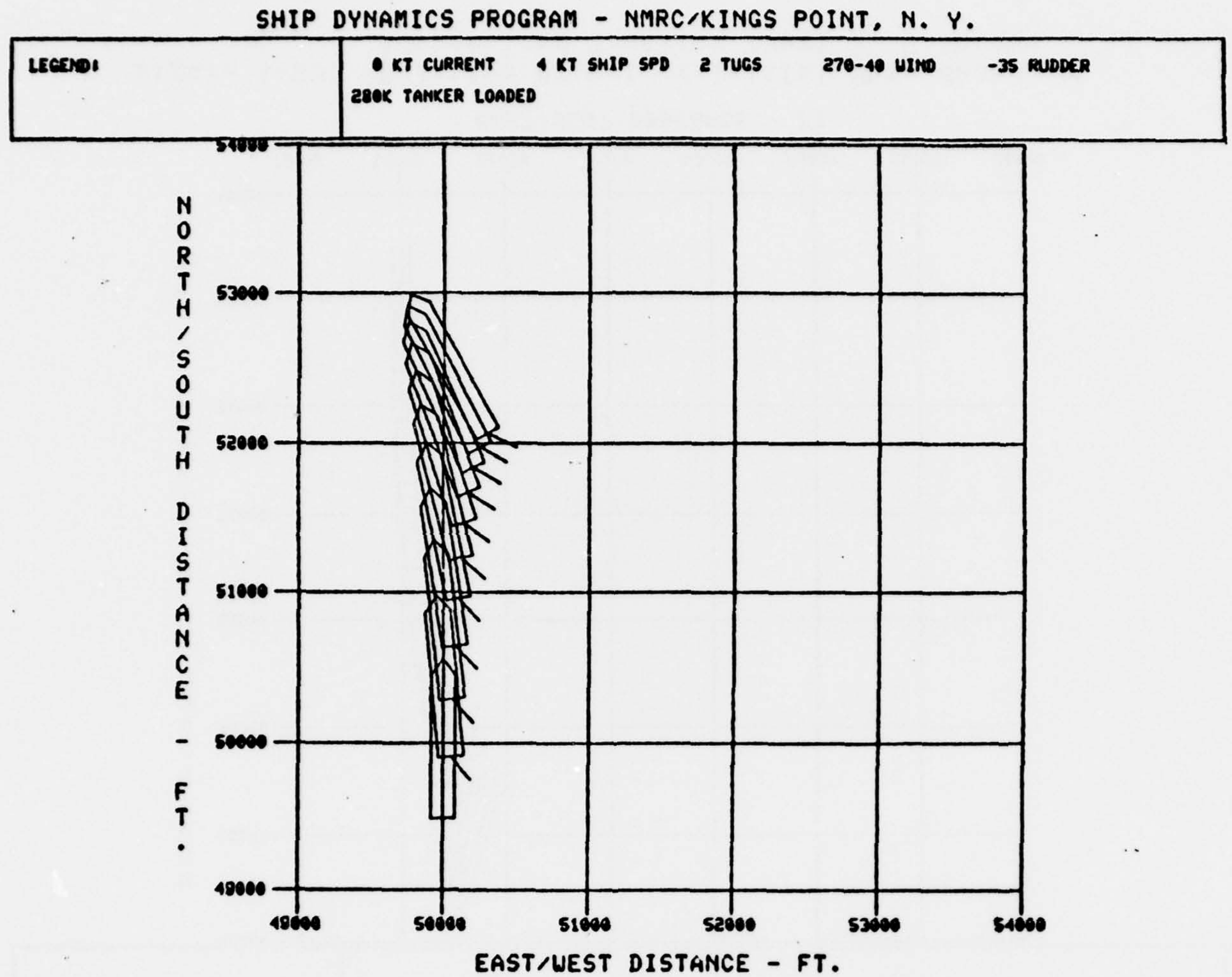

Figure 4-23. Relative Effect of Initial Ship Speed on Advance and Transfer (Part 1, 4 Knots)

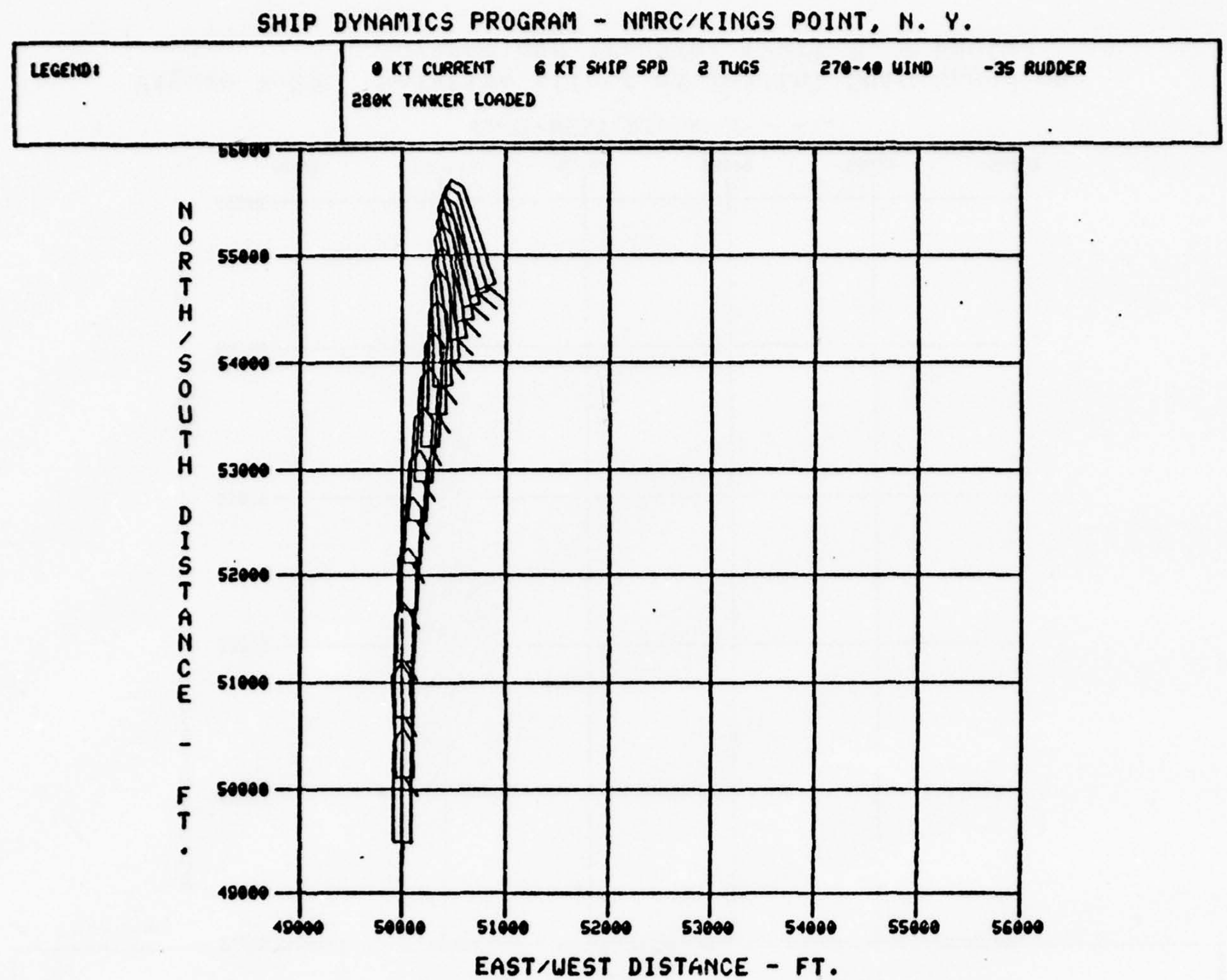

Figure 4-23. Relative Effect of Initial Ship Speed on Advance and Transfer (Part 2, 6 Knots)

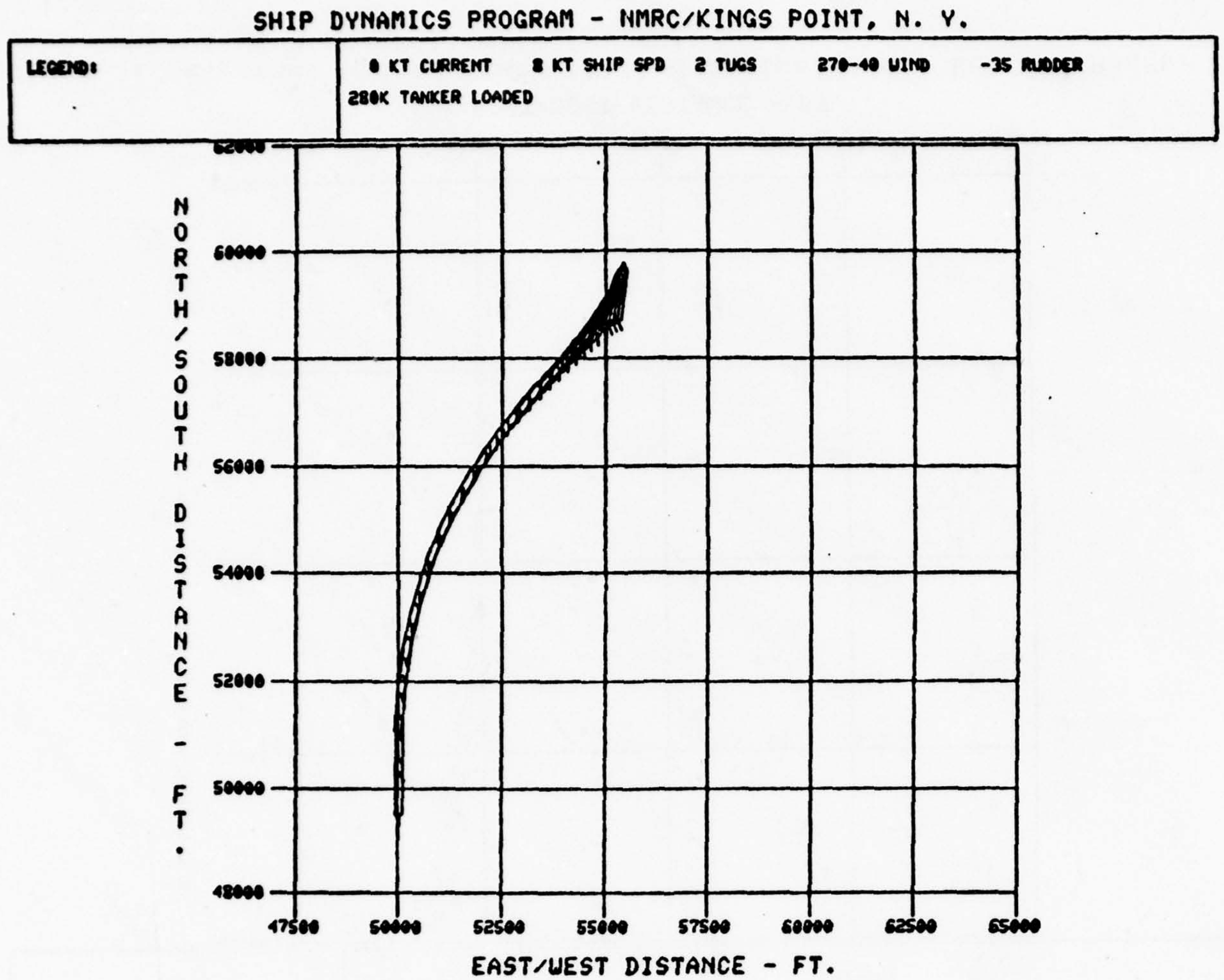

Figure 4-23. Relative Effect of Initial Ship Speed on Advance and Transfer (Part 3, 8 Knots)

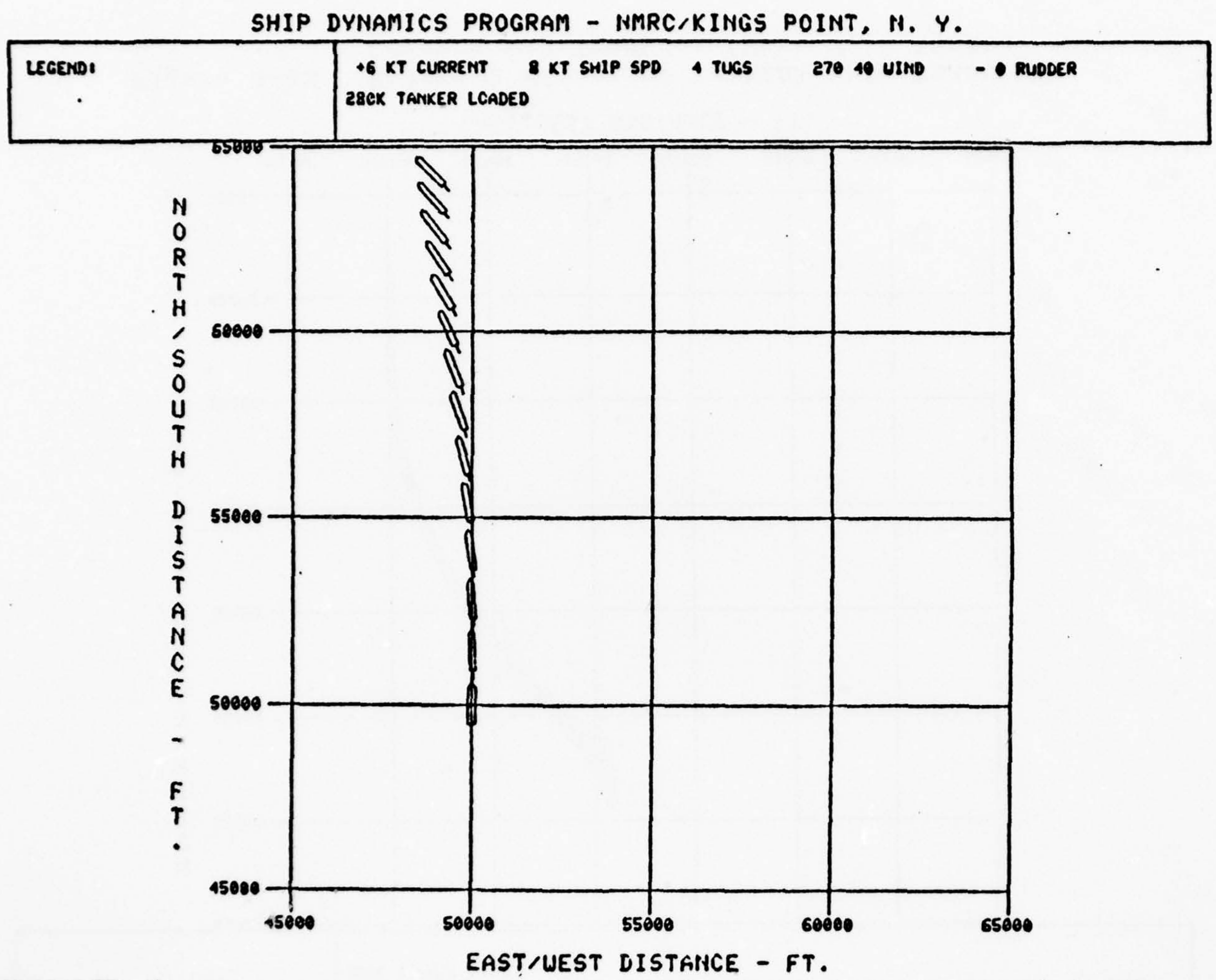

Figure 4-24. Typical Ground Track, Failed Engine/Rudder Run, 0° Rudder West Wind, Following Current

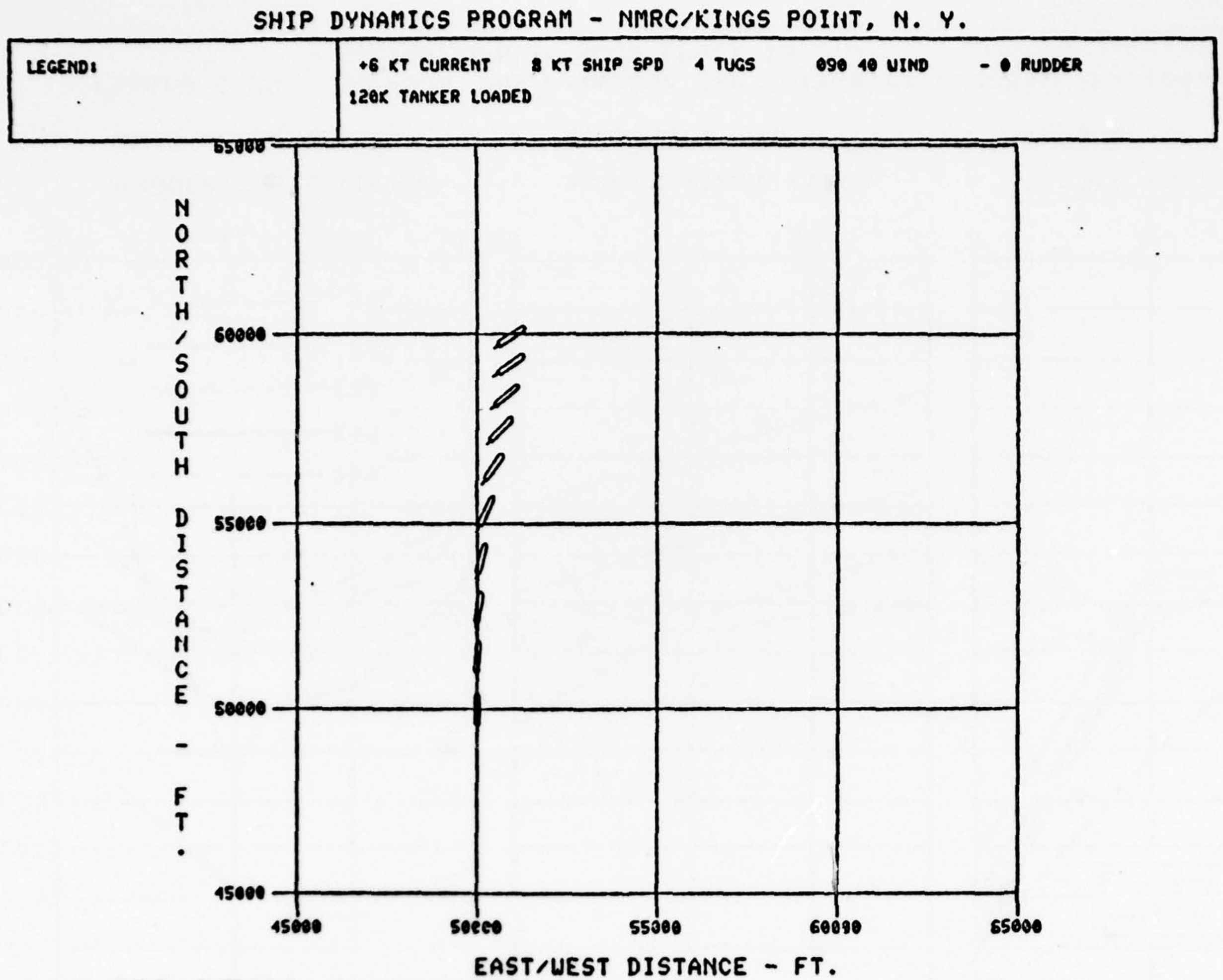

Figure 4-25. Typical Ground Track, Failed Engine/Rudder Run, 0^{o} Rudder, East Wind, Following Current

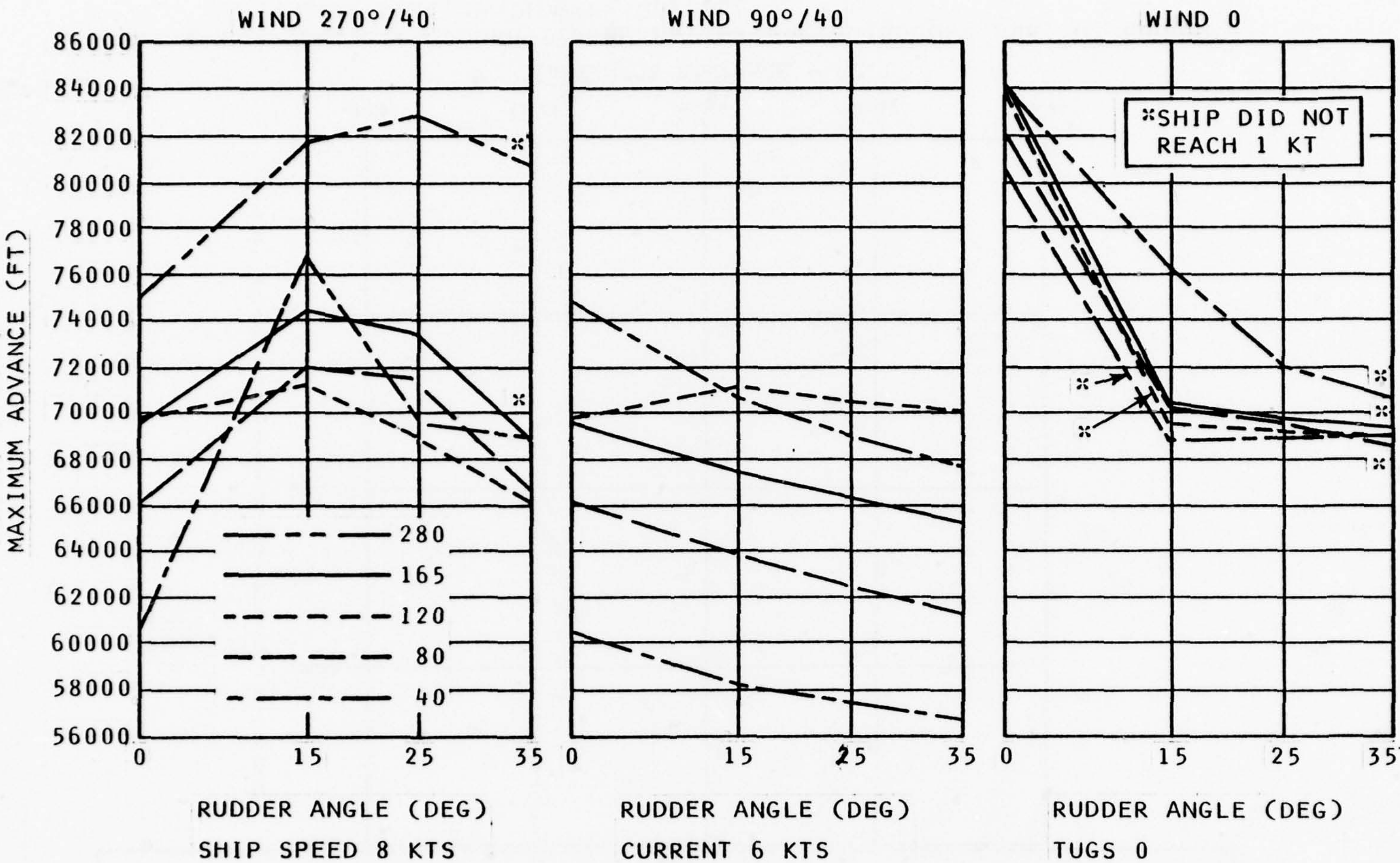

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 1)

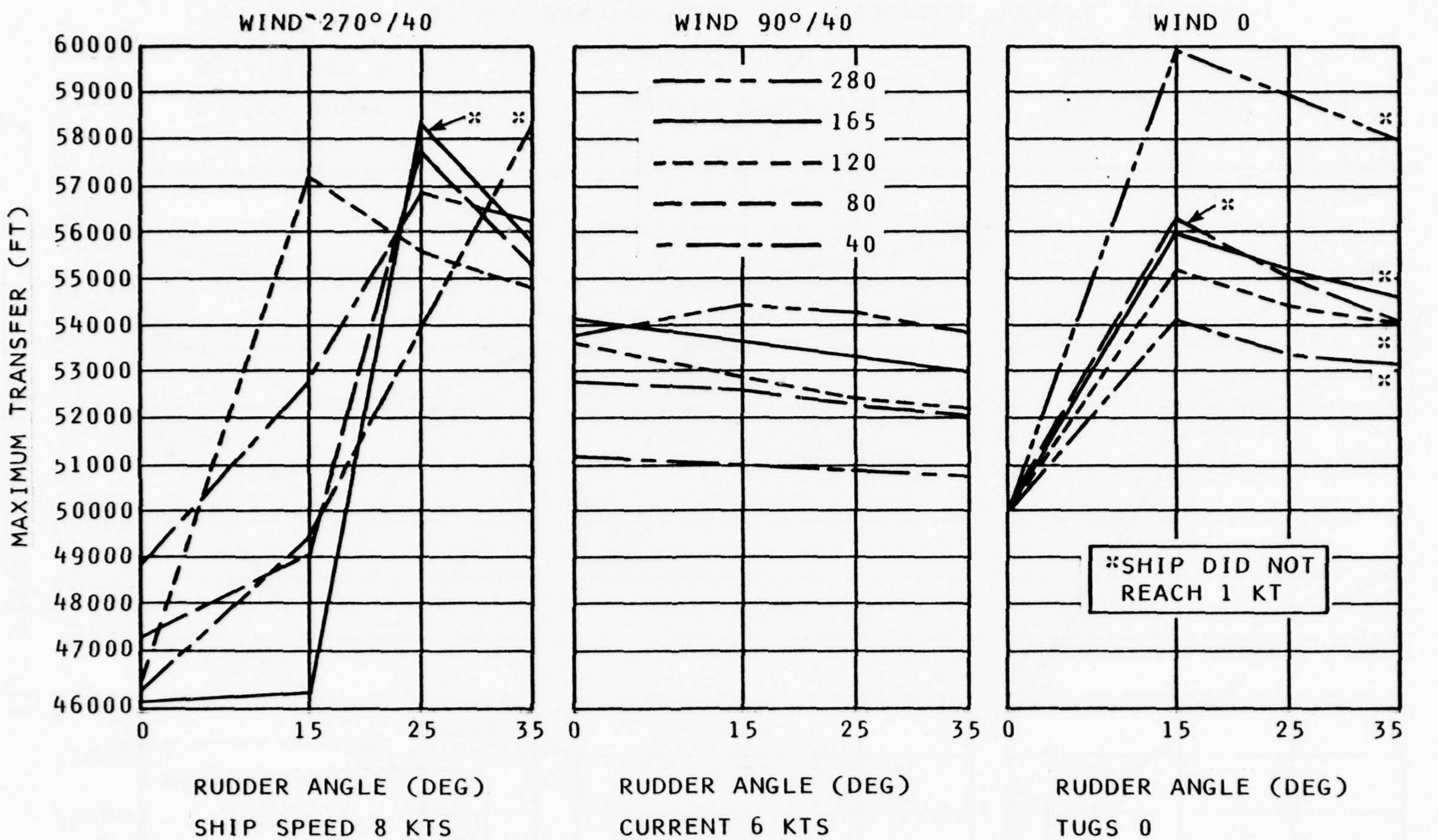

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 2)

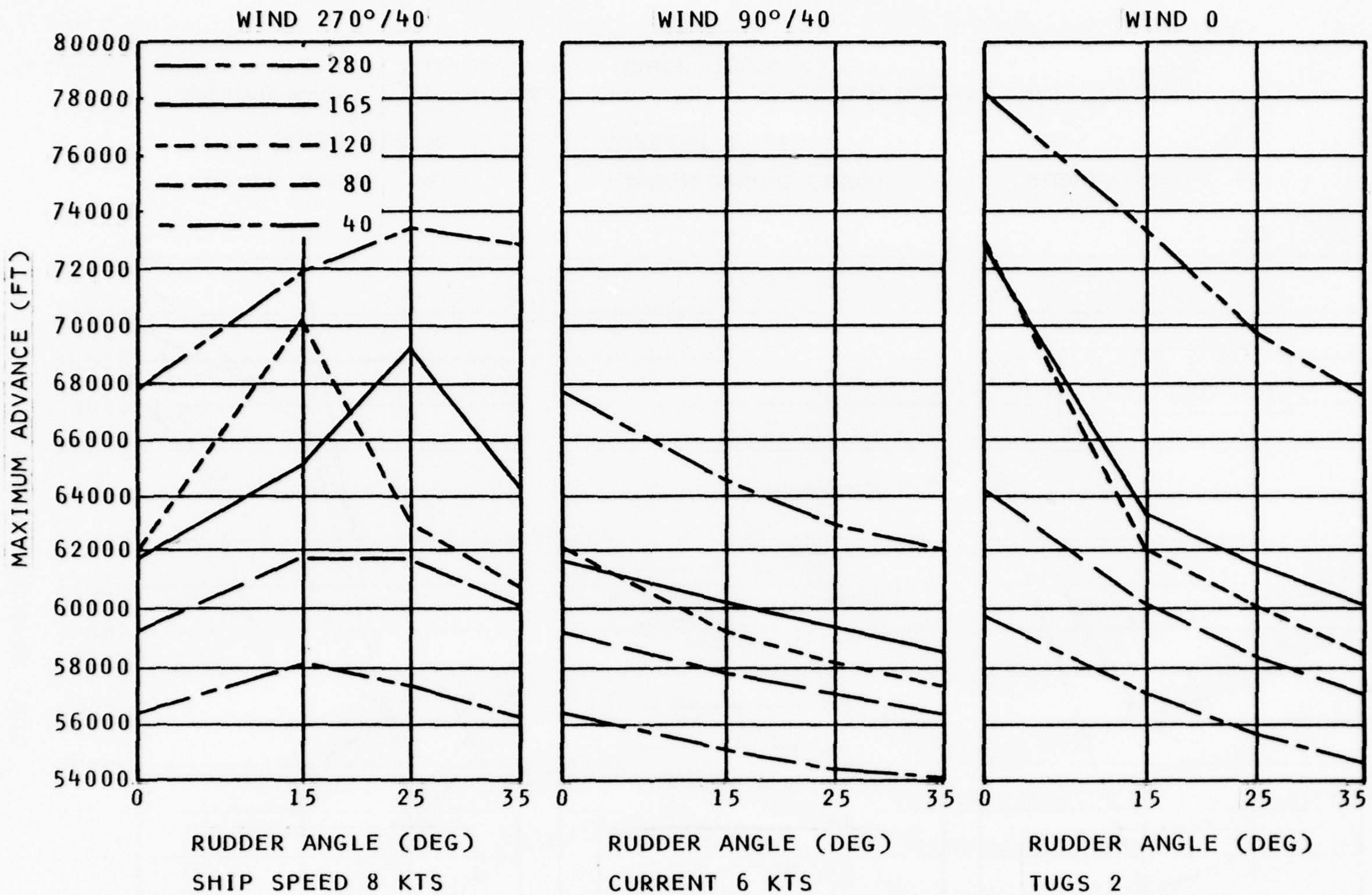

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 3)

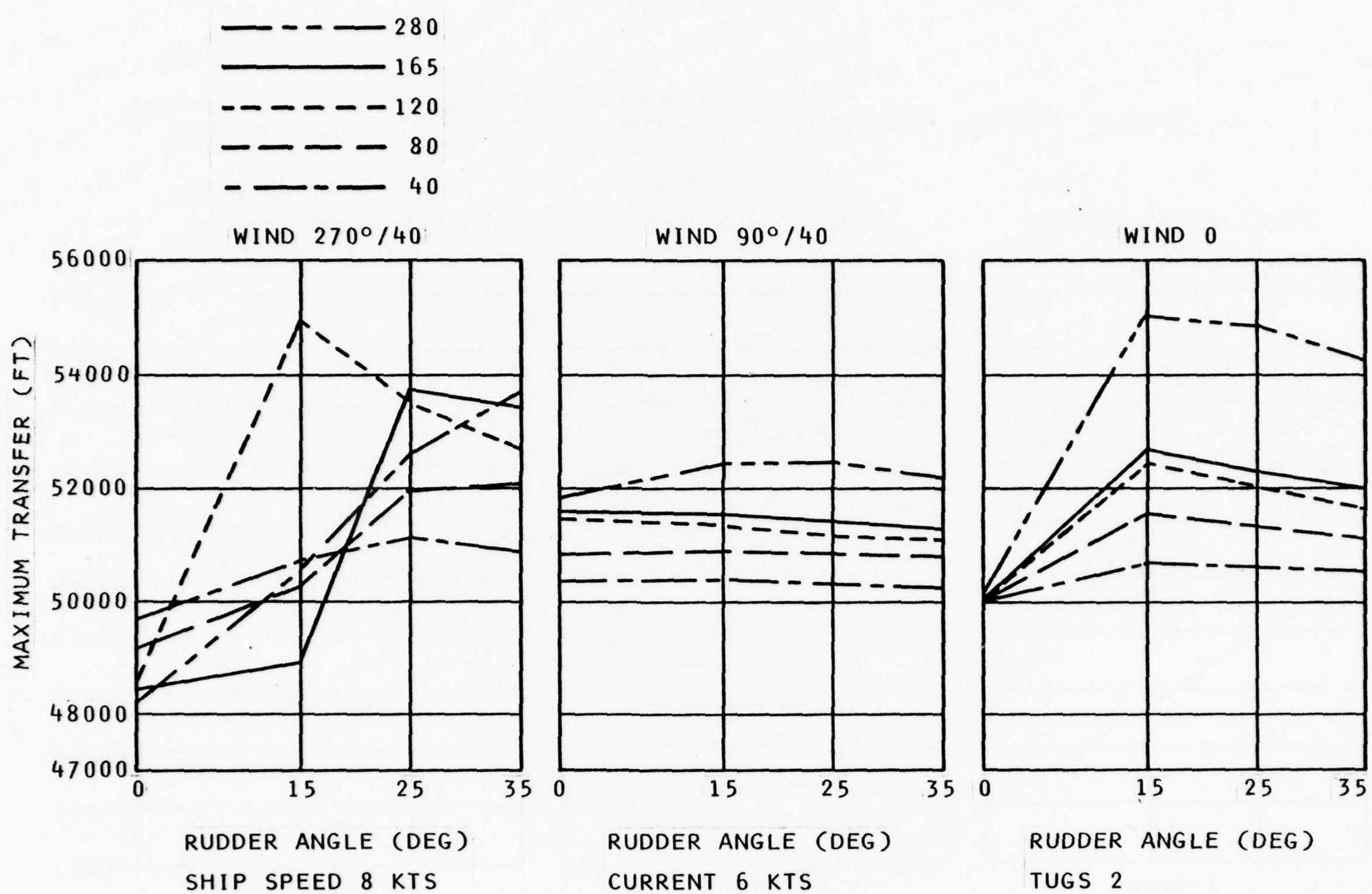

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 4)

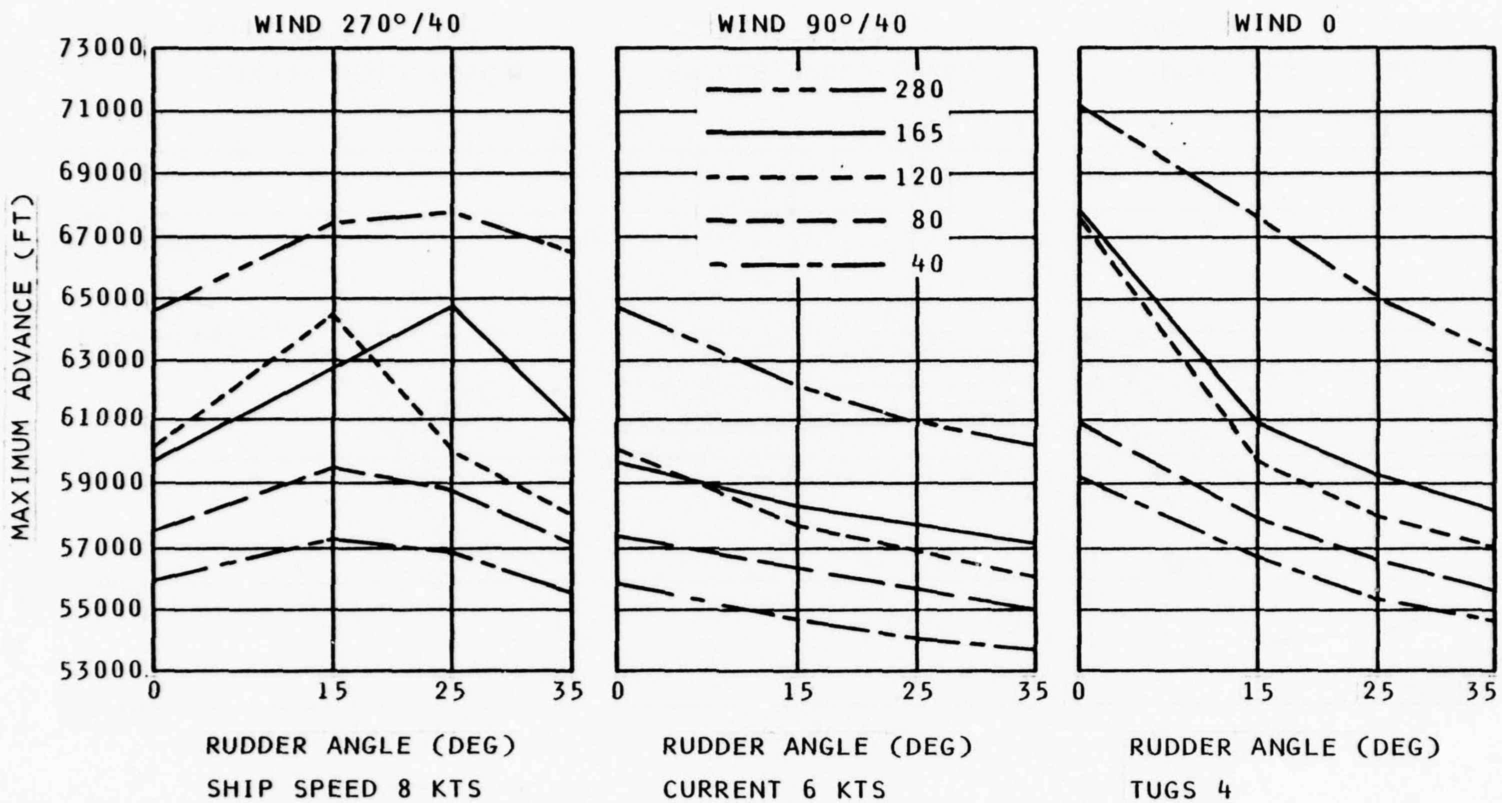

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 5)

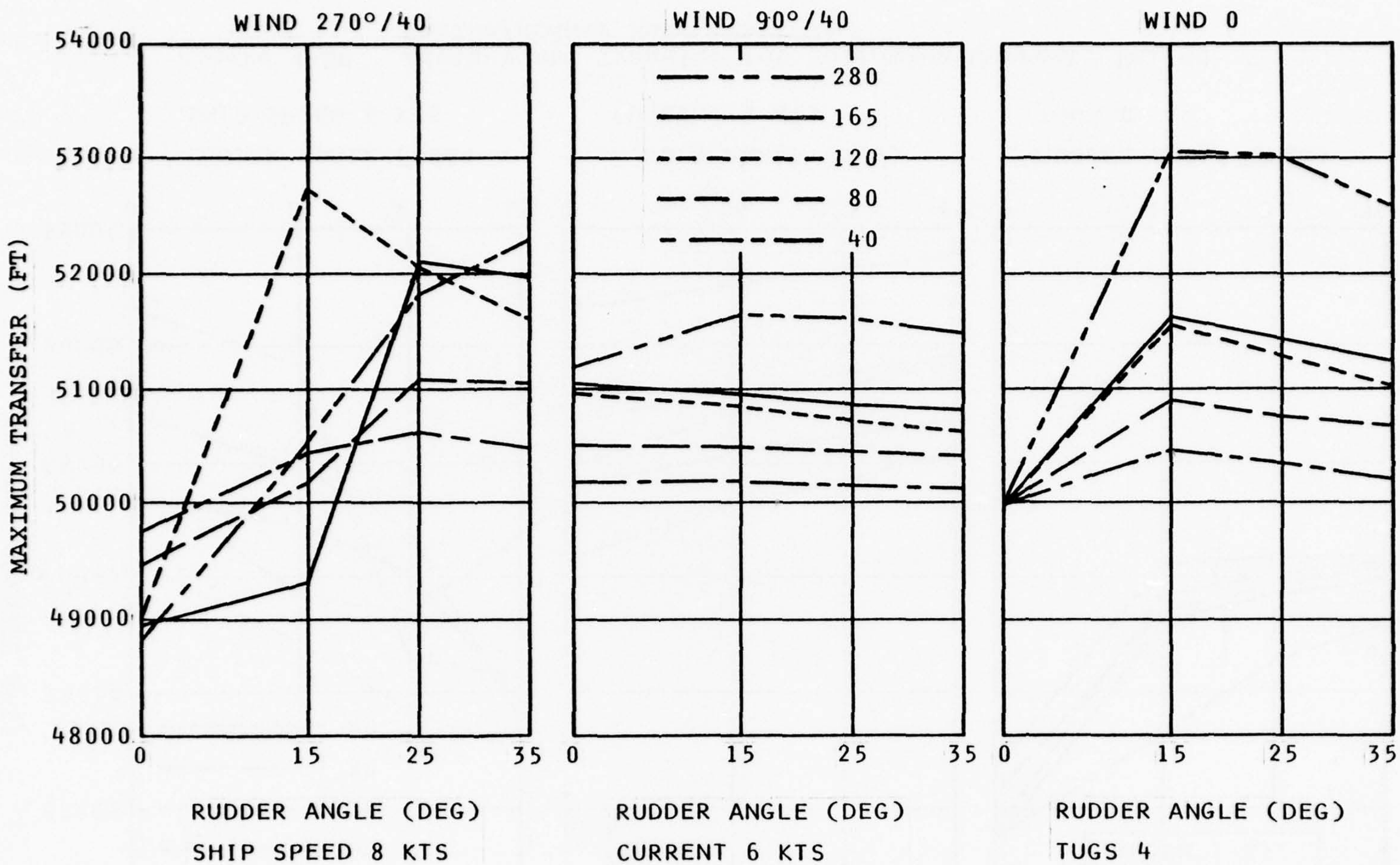

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 6)

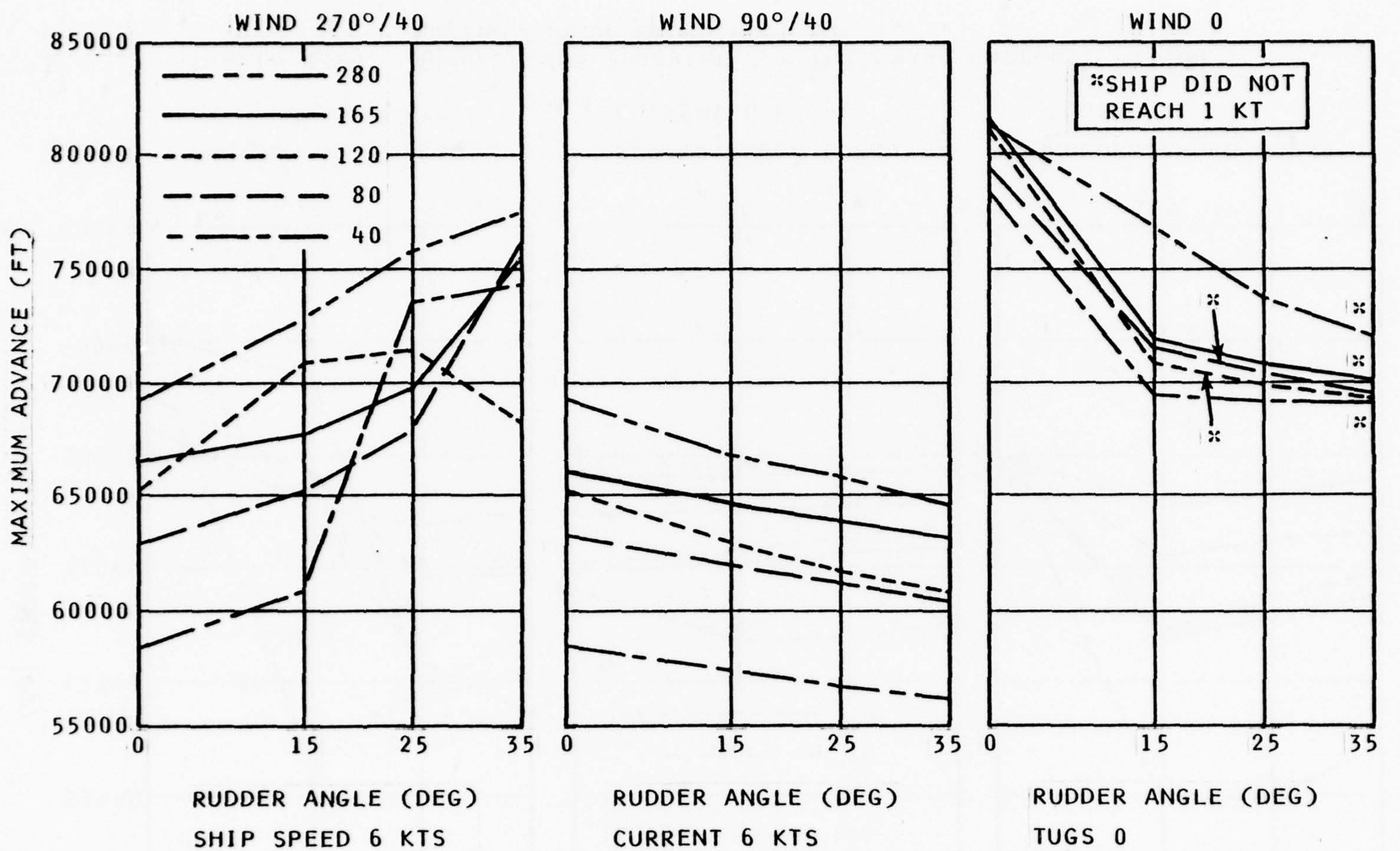

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 7)

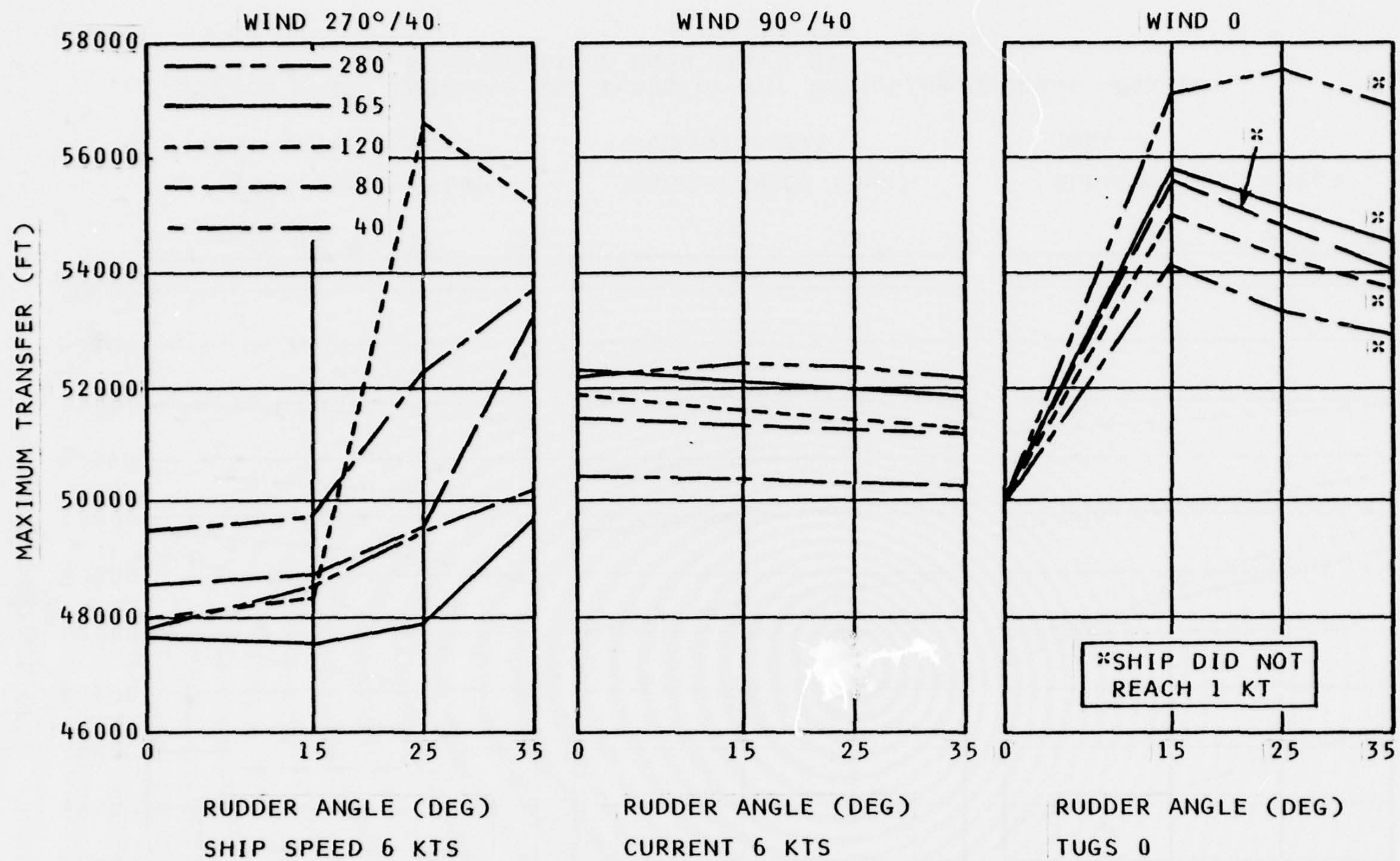

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 8)

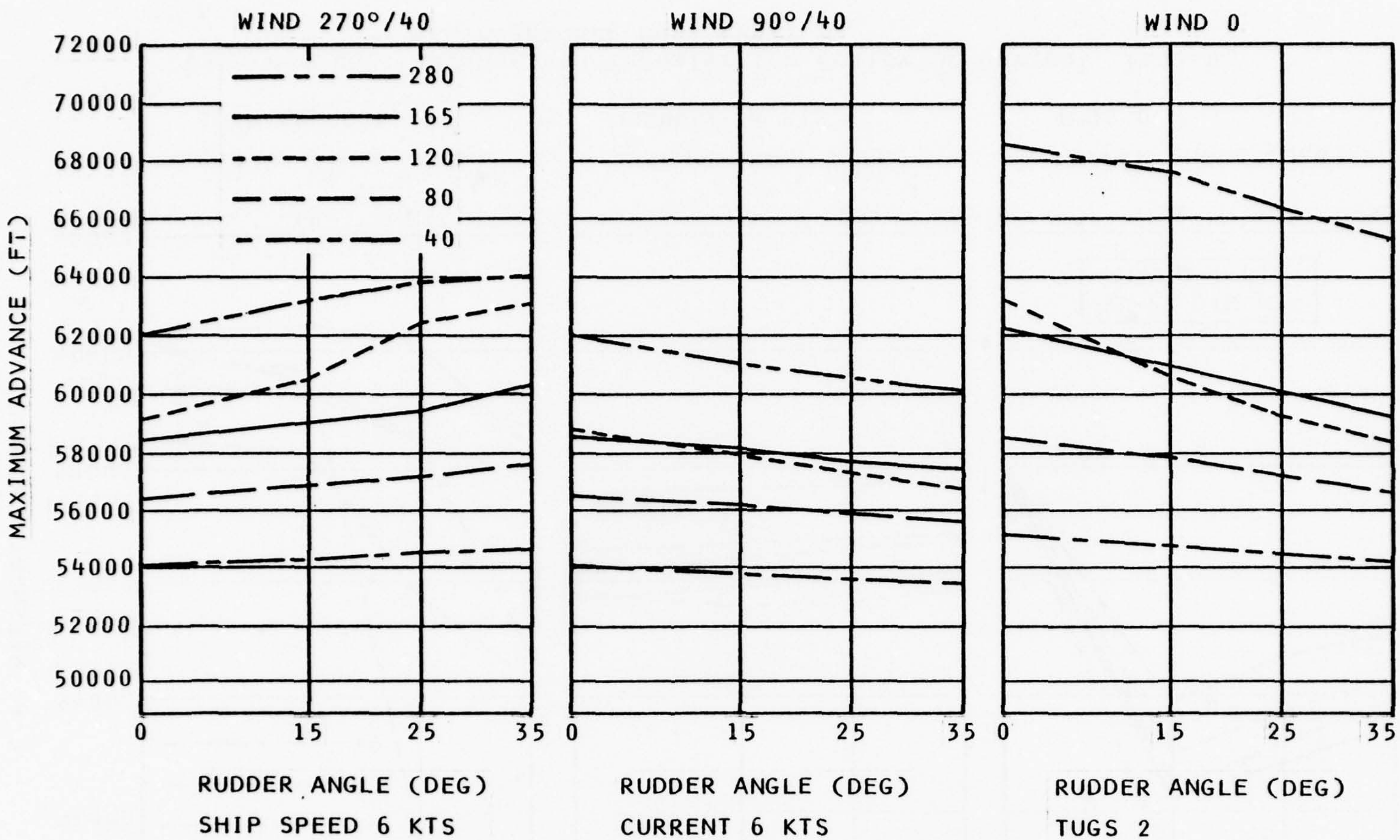

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 9)

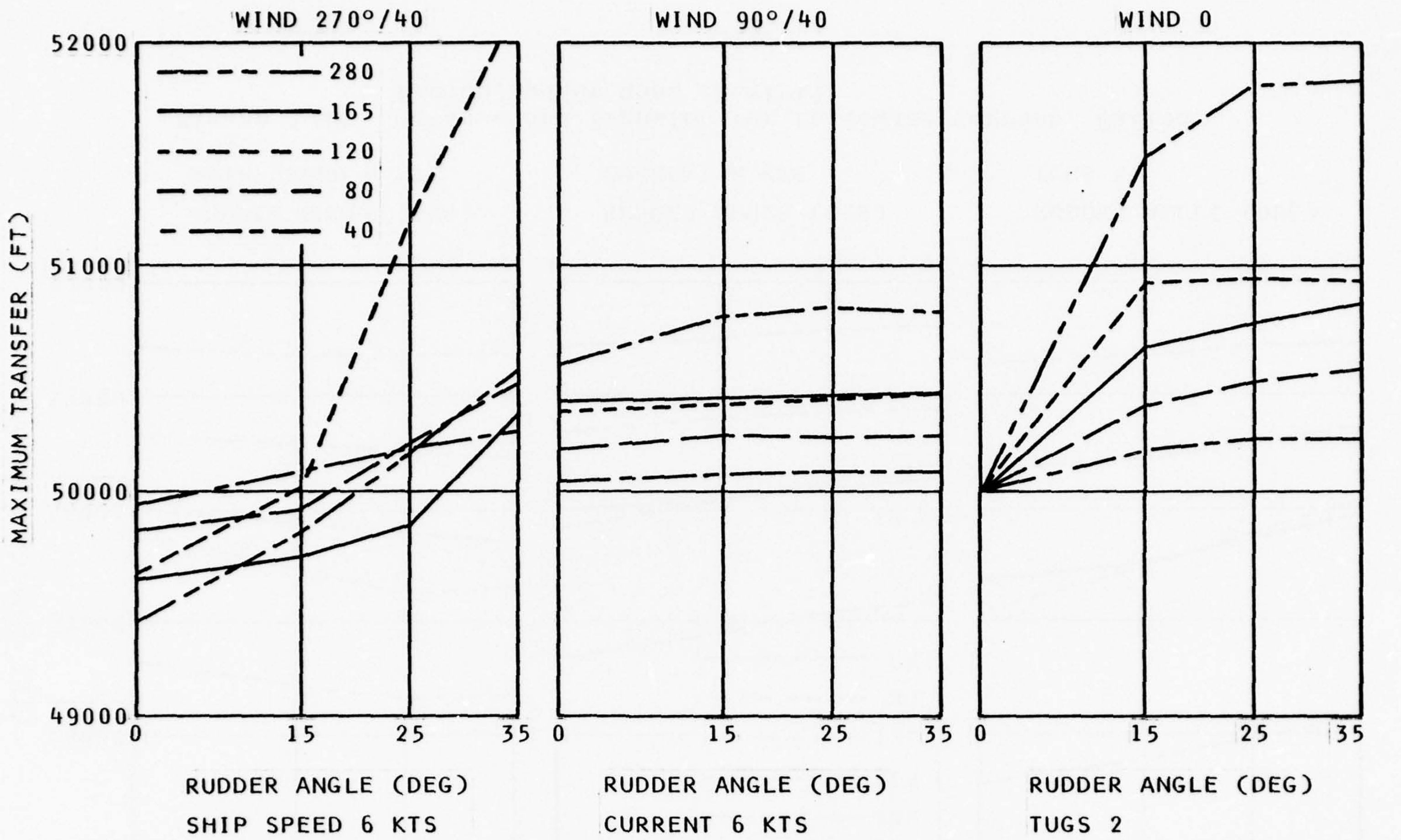

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 10)

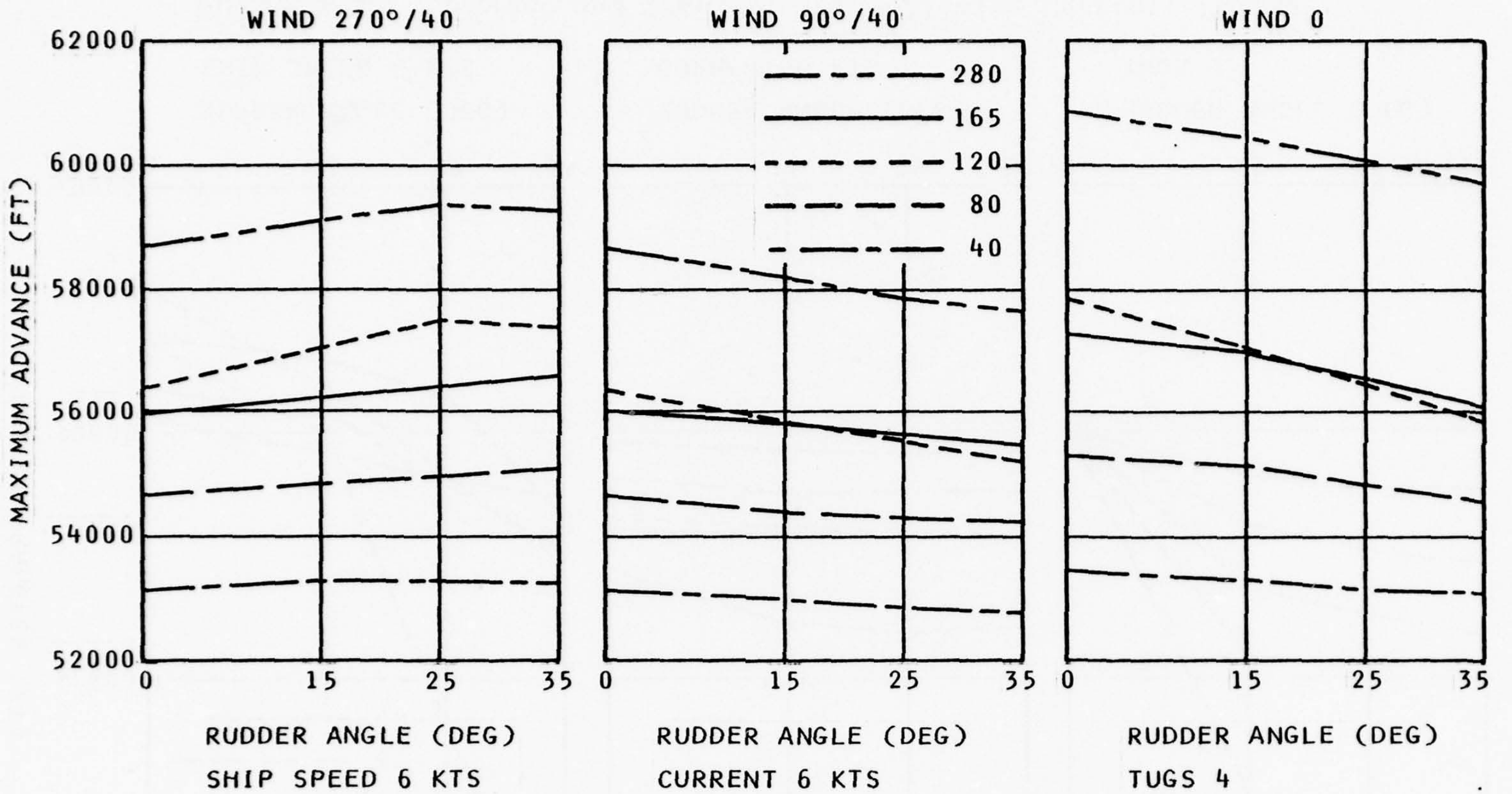

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 11)

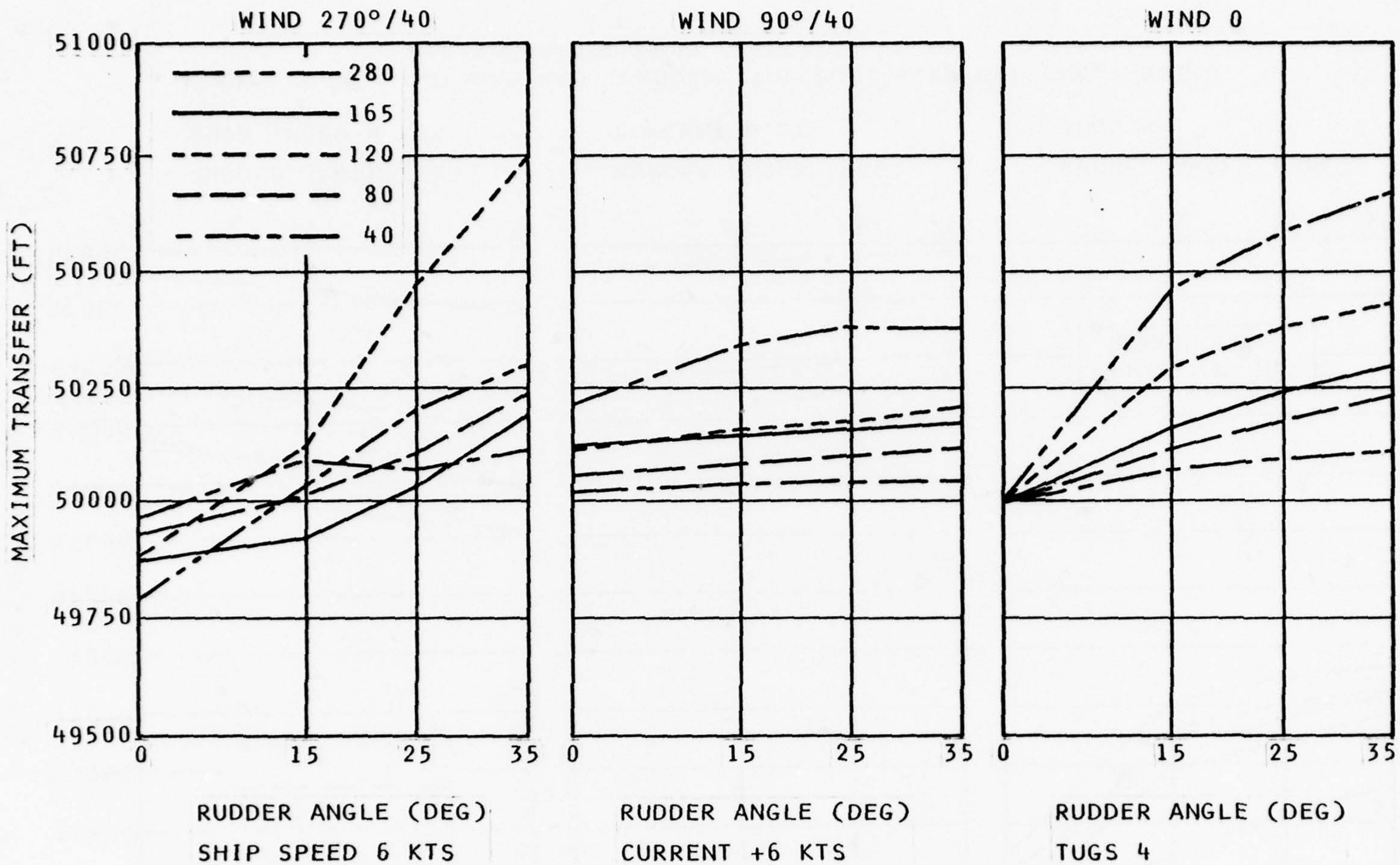

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 12)

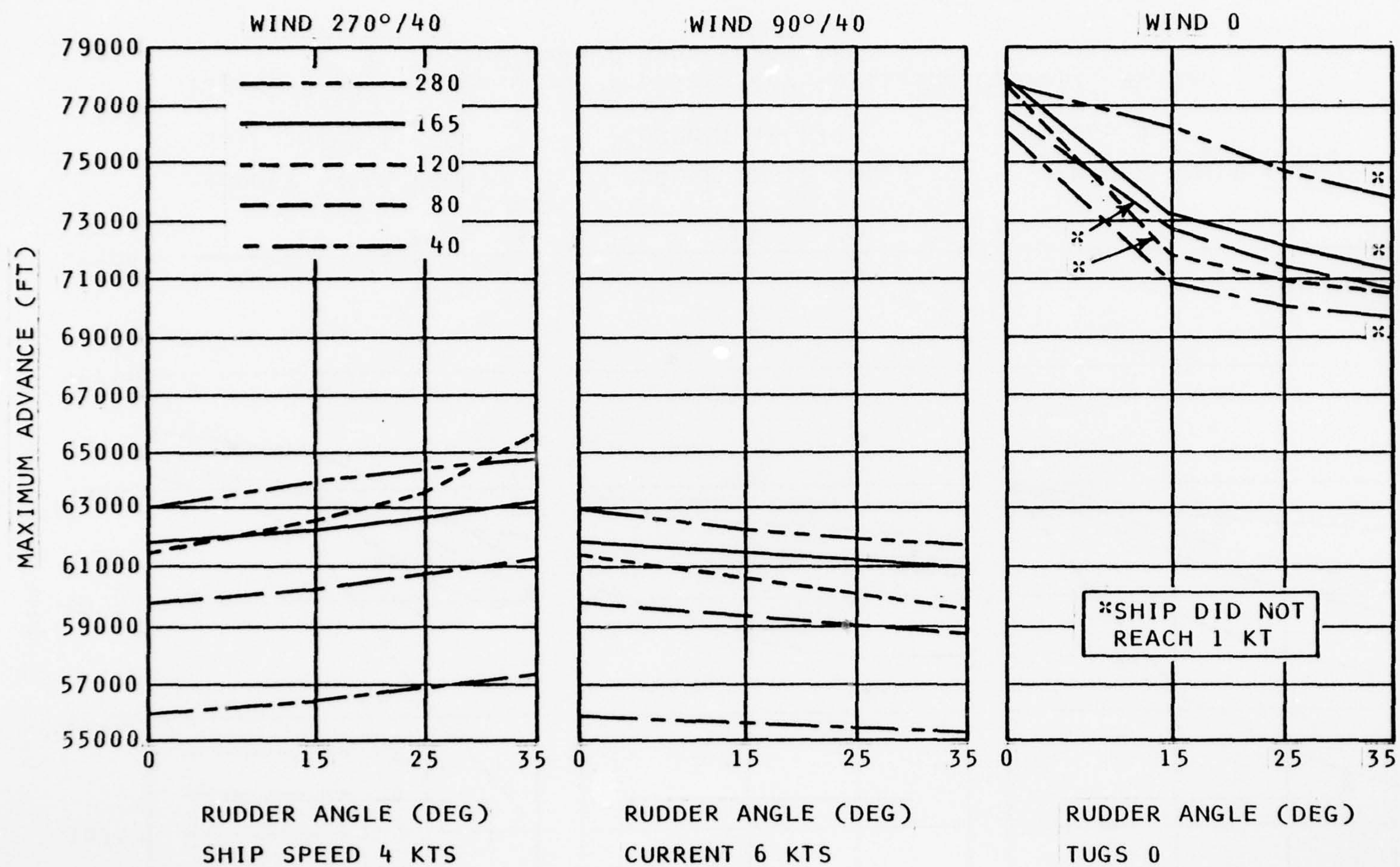

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 13)

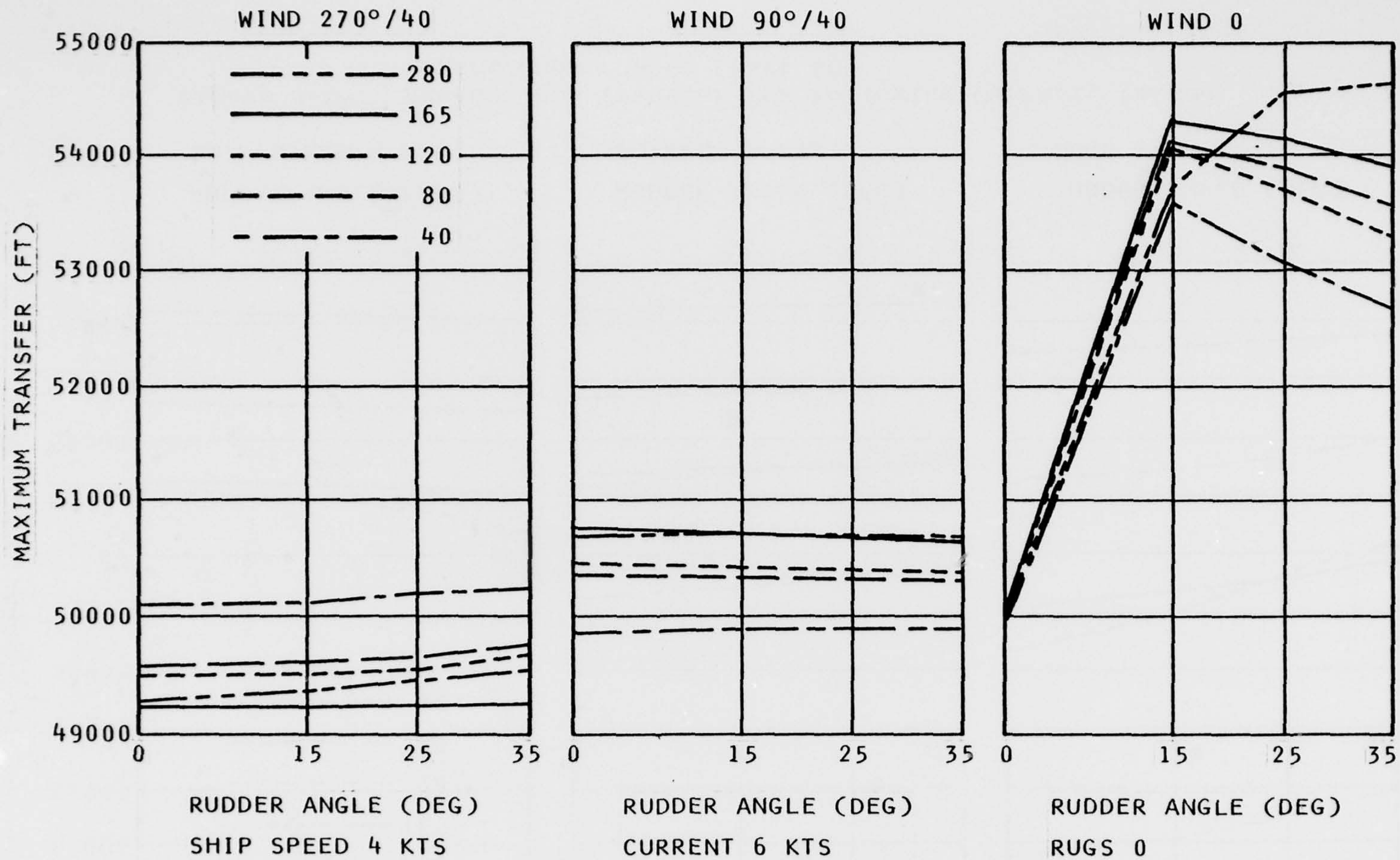

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 14)

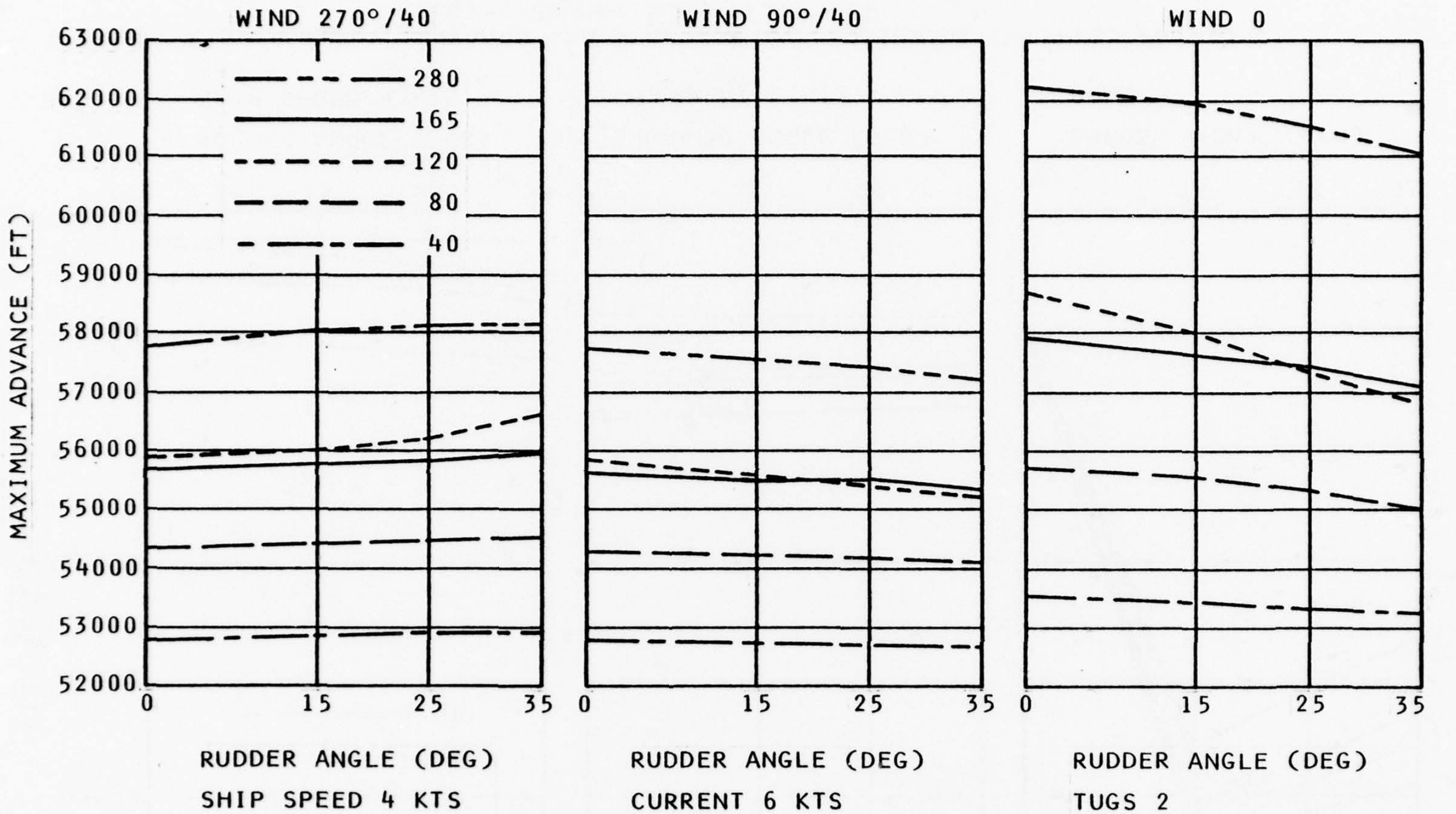

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 15)

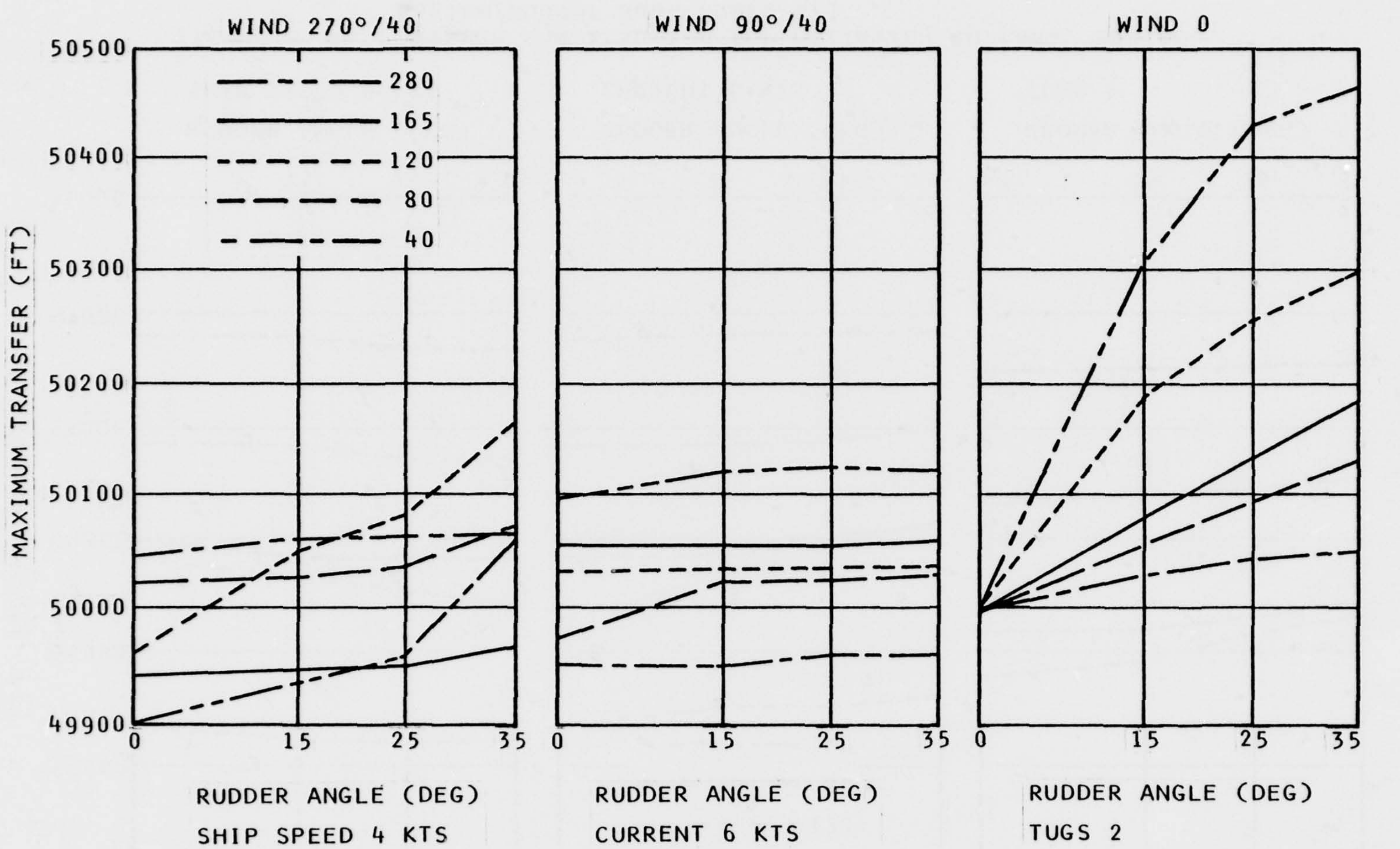

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 16)

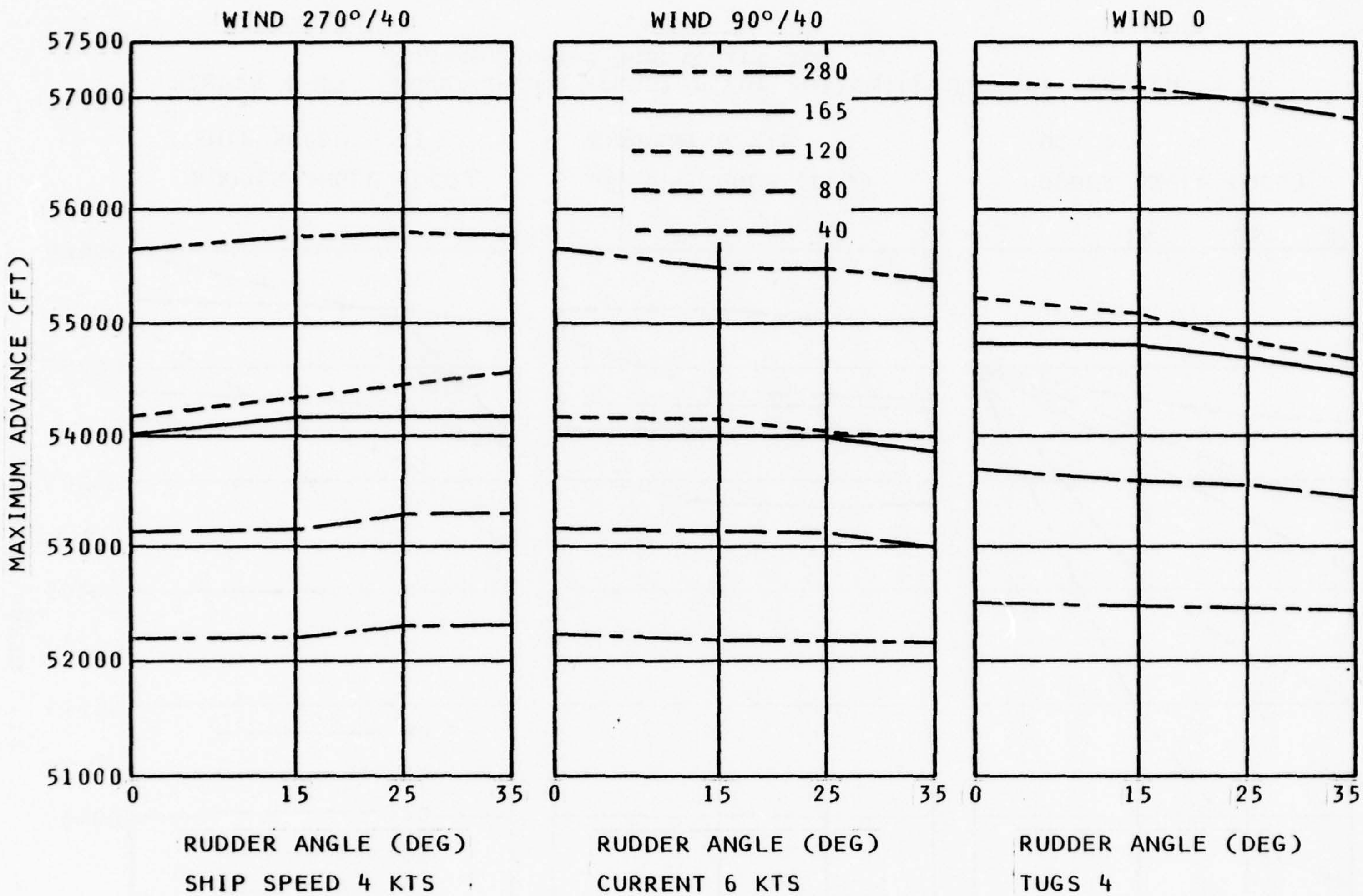

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 17)

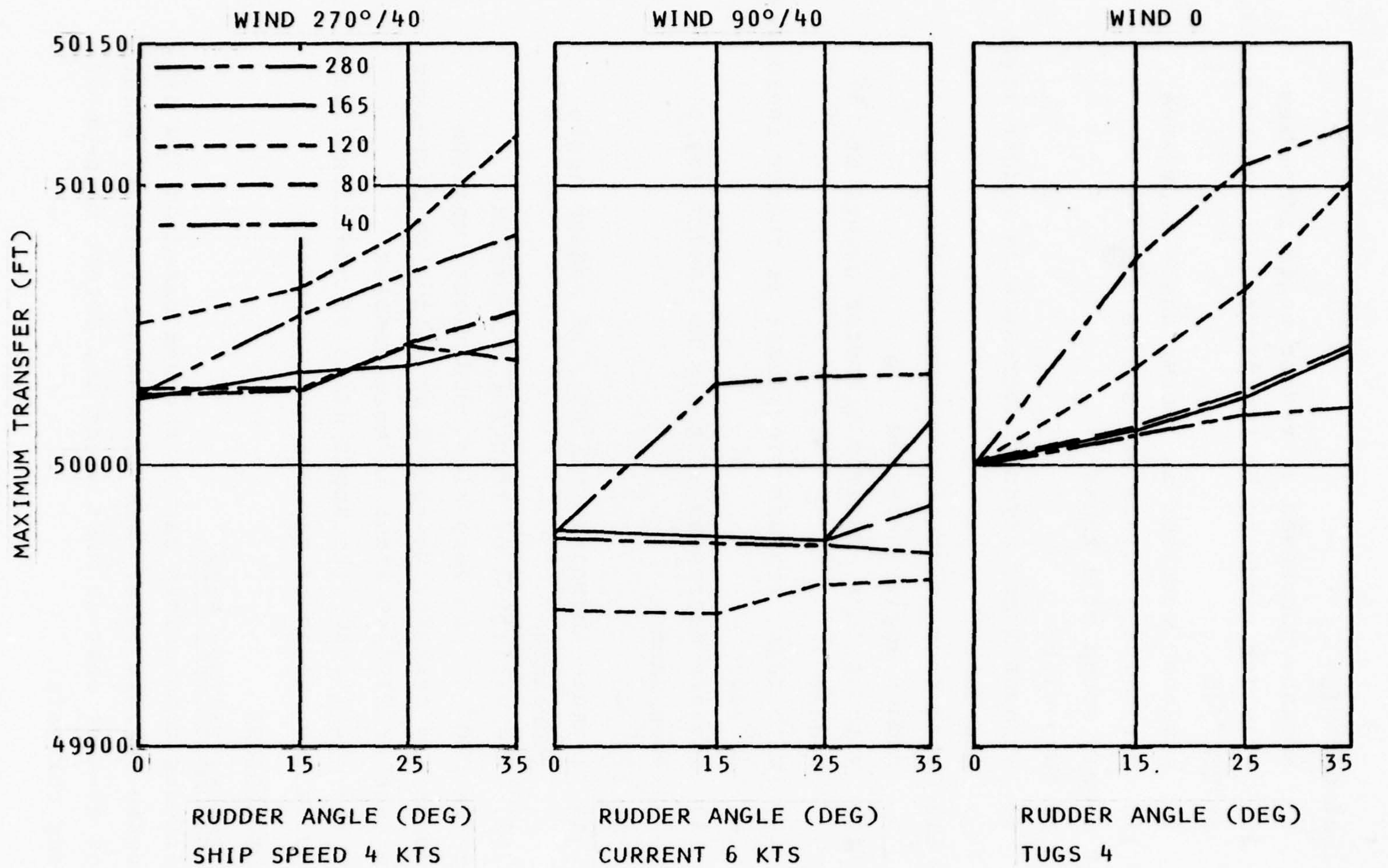

Figure 4-26. Advance and Transfer for Following Current, Failed Engine/Rudder Runs (Part 18)

b) at $090^{\circ}/40$:

i) advance decreases as rudder angle increases

ii) transfer tends to be independent of rudder angle.

c) at $270^{\circ}/40$:

i) advance increases as rudder angle increases

ii) variation of transfer is more complex.

3. For a ship speed of 4 knots:

a) at zero-wind:

i) without tugs, advance decreases as rudder angle increases

ii) with tugs, advance decreases slightly as rudder angle increases

iii) without tugs, maximum transfer occurs at 15° rudder

iv) with tugs, transfer increases as rudder increases.

b) at $090^{\circ}/40$:

i) advance decreases slightly as rudder angle increases.

c) at $270^{\circ}/40$:

i) advance increases slightly as rudder angle decreases

ii) the variation of transfer is complex.

4. For the $090^{\circ}/40$ and zero-wind conditions, maximum advance and transfer decreases as ship size decreases. The case of $270^{\circ}/40$ winds is more complex.

5. For all conditions, the application of additional tugs reduces the values of advance and transfer.

4.4 CONCLUSIONS

4.4.1 Engine Failure Runs

The following conclusions can be reached based on the off-line engine failure runs. The conclusions apply to conditions of 40-knot east or west winds and 6-knot head-on or following currents.

1. All of the vessels studied are highly susceptible to the wind at low speed. With engine failure at 4 knots, and sometimes at 6 knots, the wind consistently overpowered the rudder and turned the vessel in a direction opposite to that desired.
2. Following currents created the greatest difficulty for vessels. It was not practical to make significant changes in course; very large advances occurred during the attempted turns, and the speed over the ground remained high.
3. With a head-on current, the vessels also could not follow the desired course. However, the larger vessels with their high inertia, were able to stem the current for appreciable periods of time before drifting helplessly backwards. By turning up into the current, these vessels were also generally able to reduce their speed over the ground to speeds at which anchoring might be feasible (<0.5 knot). Varying the delay time before heading into the current demonstrated that increased delay in the time at which the vessel is turned up into the current results in greater transfer and also reduces the amount of time at very low speeds over the ground available for anchoring. The larger the vessel, the longer the time delay it can tolerate before a turn-up-into-the-current becomes of little or no advantage.
4. The inability of all the vessels to consistently establish speeds over the ground at which anchoring may be attempted, and the difficulty of maintaining control in a turn, suggest that tug support is needed to guarantee safety in the event of engine failure.

4.4.2 Engine/Rudder Failure Runs

The following conclusions can be reached based on the off-line combined engine/rudder failure runs with tug assistance provided. The conclusions apply to 40-knot east or west winds.

1. The use of tugboats to retard the forward motion of the vessel results in an appreciable reduction in the distance traversed and the transfer. In general, a significant benefit occurs with the application of the first two tugboats. The incremental improvement provided by two additional tugboats is not as great.
2. High magnitudes of transfer occur at ship speeds through the water of 8 knots or more. Tugboat utilization strategies other than pure retardation are required if lower transfers are to be achieved at these speeds.
3. At speeds through the water less than 8 knots, reasonable magnitudes of transfer can be achieved with retarding tugs. However, these lower speeds may conflict with the requirements for satisfactory track-keeping when extremes of current and wind exist.

4.5 RECOMMENDATIONS

1. Further analysis of the combined engine/rudder failure data should be carried out to determine whether tugboat utilization strategies, other than their use as pure decelerators, can bring the transfer values down to consistently safe values at 8 knots, or higher speeds through the water.
2. Research and development effort should be expanded to create realistic models of tugboat usage that can be used in off-line studies. An interactive system with CRT delay capabilities which permits study of tug techniques, should be considered.
3. The impact of the use of modern tugs, such as tractor tugs which can exert appreciable lateral forces at high forward speeds, should be studied.
4. Vessels should be equipped with speed-over-the-ground/through-the-water instrumentation (e.g., Doppler speed log) to help pilots and masters determine when feasible anchoring speeds are reached in emergency situations.

SECTION 5

CAORF MAN-IN-THE-LOOP SIMULATION

5.1 INTRODUCTION

The purpose of running the man-in-the-loop experiments was to provide a sample comparison between results of the mathematical off-line study and results from actual human behavior. Four test subjects were used, two of which were practicing Puget Sound Pilots and two were New York Harbor Sandy Hook Pilots with no experience in Puget Sound. The model used on the simulator was the 165,000 DWT tanker. Each test subject was provided familiarization training on the simulator and then performed a total of 7 or 8 exercises presented in random order.

5.2 RUN METHODOLOGY

Each run required an initialization procedure to be executed. This involved maintaining control of the ship while the wind and current forces were entered into the simulator so that after a brief stabilizing period (1 or 2 minutes), command of a smooth-sailing, under-control tanker could be given over to the pilot for continuation of the runs. During this 1 to 2 minute period, the pilot was briefed by the mate on watch as to the nature of the run (destination, etc), the environmental conditions, allowable ship speed through the water, and availability of tugs.

There were two types of simulator runs made: track-keeping and failed equipment. All track-keeping runs were performed in either Rosario Strait or Haro Strait (near Turn Point). All failed equipment runs took place in Haro Strait in Boundary Pass. In all cases, ship speed through the water was to be maintained at 4 or 6 knots (plus or minus 1/2 knot).

Failure conditions were of two types: engine or combined rudder and engine. The time of failure was dependent upon ship speed. In a 4-knot run, failure time was 22 minutes after start. In a 6-knot run, failure time was 18 minutes after start. When taking account of current, it can be seen that these two failure times correspond to approximately the same location in Boundary Pass.

Engine failure was defined as setting the RPM to zero. Rudder failure was defined as setting the rudder to hard right (-35°).

Two tugs, already made up on soft lines, were permitted to be used only in the combined rudder and engine failure runs. In such cases, the appropriate time delays were imposed, and the tugs could be used only for backing astern at whatever power was commanded by the pilot. The two tugs were constrained to operate at the same power settings astern and thus all tug forces were directed 180° relative to the tanker's heading. The use of "steering tugs" or any other such modification was not permitted.

5.3 PLOTS OF SHIP TRAJECTORIES

Following each run, a plot of the ship's ground track was made (see Figure 5-1). The ship position is plotted at 2-minute intervals and the conditions under which the run was made are contained in the upper right-hand corner of the sheet. The upper left-hand corner contains a coded description of the geographic area and ship speed. The key to the code is:

ROS 4 (ROS6) = Rosario Strait at 4 knots (6 knots)

HARO 1/4 (HARO 1/6) = Haro Strait near Turn Point at 4 knots (6 knots)

HARO 2/4 (HARO 2/6) = Haro Strait in Boundary Pass at 4 knots (6 knots)

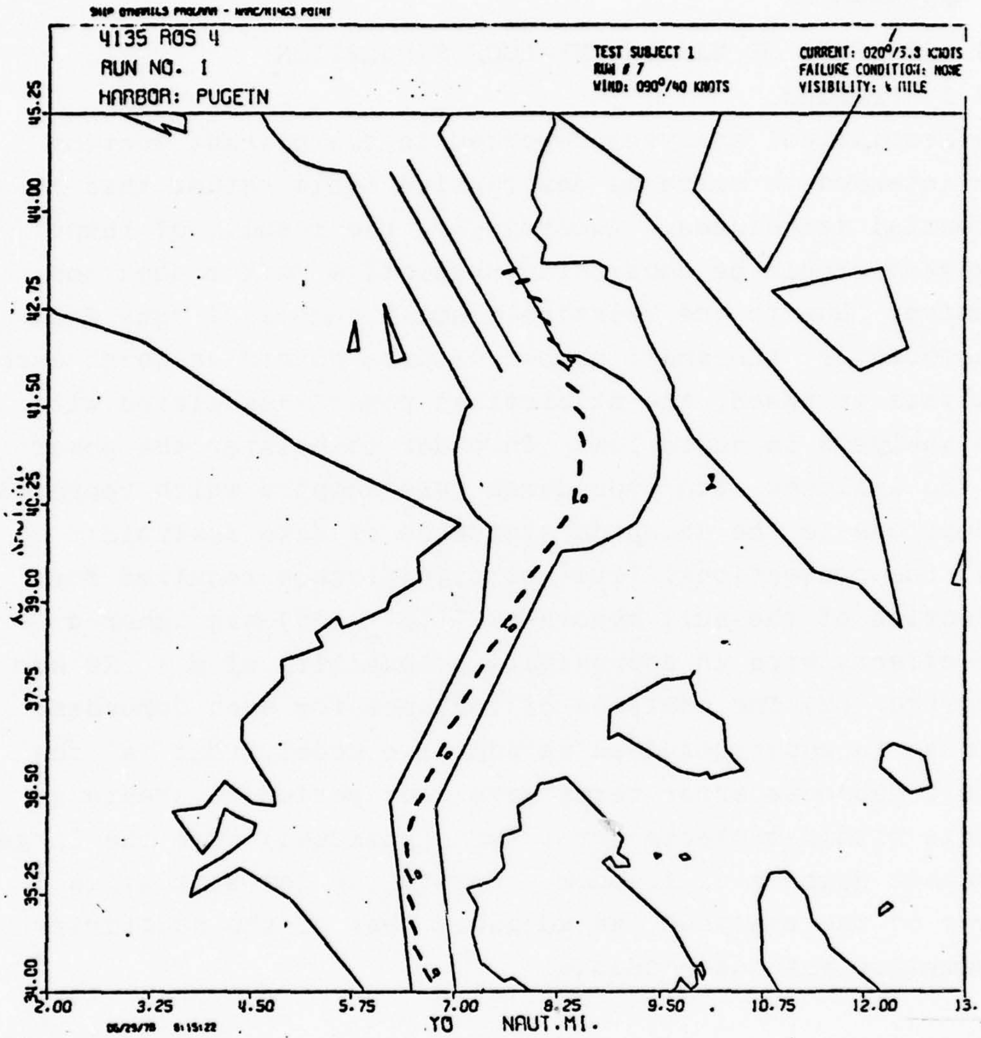

Figure 5-1. Typical Ship Ground Track Plot: Man-in-the-Loop Run.

The plots for all test subject and all runs are contained in Appendix E.

5.4 ANALYSIS OF MAN-IN-THE-LOOP SIMULATION

5.4.1 Preface

The statistical analyses reported in the present section are intended to serve as descriptive tools rather than inferential techniques. Accordingly, the results of these analyses should be considered suggestive rather than conclusive. Due to the relatively small number of runs and, consequently, the small number of data points on which each analysis is based, the statistical power[1] associated with the analyses is quite low. In order to bolster the power of the analyses, two procedures were adopted which represent exceptions to the accepted standards of data analysis: (1) the conventional level of significance required for rejection of the null hypothesis[2] ($p \leq .05$) was ignored and effects with an approximate probability of $p < .20$ are reported. (2) The analysis of variance for each dependent measure is constructed as an additive model; that is, the within-subjects error terms have been pooled to create a single within-subjects error term (residual) with the largest possible degrees of freedom. Due to the low statistical power of the analyses, an adequate test of the additivity assumption was not possible.

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[1] The statistical power of an analysis is defined as the probability of rejecting a false null hypothesis (i.e., that there is no true effect due to the factor under consideration) in favor of an alternative hypothesis which specifies an effect of a given magnitude. Power increases as a direct function of sample size, degrees of freedom associated with the estimate of error variance and effect magnitude.

[2] The level of significance associated with an observed effect is defined as the probability of obtaining by chance an effect at least as large as that observed assuming no true effect exists. For example, an effect described as significant as $p < .05$ means that the probability of observing by by chance an effect that large is less than 5 out of 100.

5.4.2 Performance Measures

Three sets of dependent measures were collected over the course of each simulator run: (1) The frequency of course, rudder, and RPM commands and the frequency with which bearings were taken were obtained from the first mate's logs of bridge activity. (2) Measures of the average value and the variability of rudder angle and ship speed were derived from the computer-maintained data log. (3) Closest-point-of-approach (CPA) to selected points of land for each of the run locations was determined from the plots of each run.

5.4.3 Description of the Analysis Procedure

For each dependent measure listed above an analysis of variance was computed in order to assess the effects of pilot home port (Sandy Hook vs. Puget Sound), ship speed (4 kts. vs. 6 kts.), and run location (Rosario Strait vs. Haro Strait) on the dependent measure. In addition, the analyses tested for the possibility of interactive effects between the independent variables and the dependent measures. For example, if the effect of ship speed on CPA were quite different in Rosario Strait than in Haro Strait, a significant interaction of ship speed and run location would be obtained. In the following summary of results, only those effects which approached significance ($p < .20$) are reported. Possible effects which are not discussed were clearly insignificant.

5.4.4 Summary of Results for The Track-keeping Runs

5.4.4.1 Effects of Home Port

1. Bridge Activity

   (See Figure 5-2). Relative to the Puget Sound pilots, Sandy Hook pilots tended to give fewer course commands ($p < .20$), give more rudder commands in the Rosario Runs ($p < .10$), give more RPM commands ($p < .10$) and take bearings more frequently ($p < .05$).

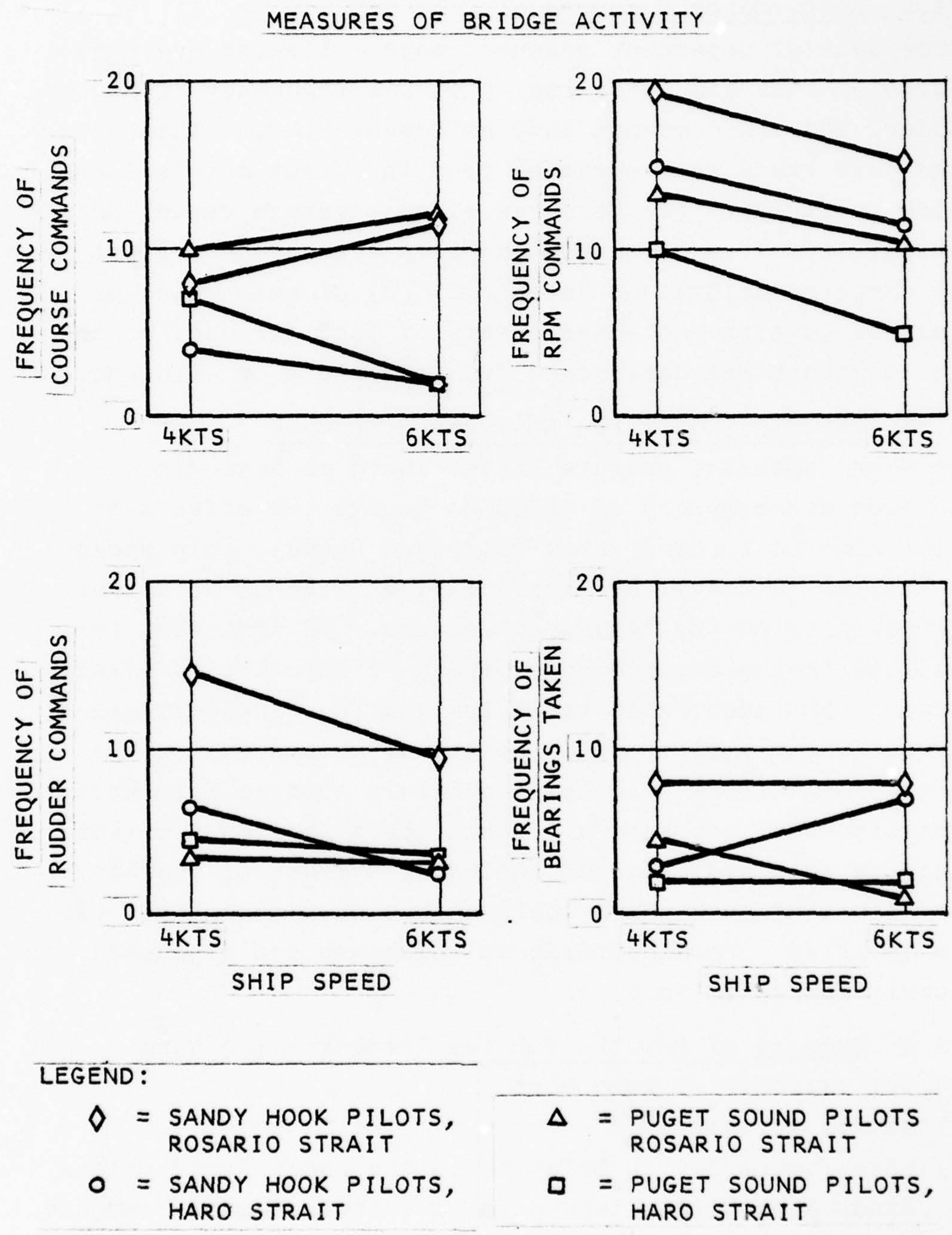

Figure 5-2. Measures of Bridge Activity

That such behavioral differences should exist is not unexpected. The New York Harbor area familiar to the Sandy Hook pilots tends to be more crowded with traffic and confined than the Puget Sound area. In such confined areas, rudder commands are more common than course commands in order to maintain greater control over the vessel. The Sandy Hook test subjects simply carried over this learned behavior to the Puget Sound area. Sandy Hook pilots could also be expected to take more frequent bearings since they were not so familiar with the simulated areas.

2. Ship Performance Measures (Rudder Angle and Ship Speed Measures)

(See Figure 5-3). The greatest standard deviation (variability) ($p < .10$) of ship speed occurred for the Puget Sound pilots in the 6-knot runs through Haro Strait.

All the pilots agreed, subjectively, that the tanker was generally difficult to control at 4 knots but more easily controlled at 6 knots. For the track-keeping runs in Haro Strait near Turn Point, the environmental conditions created severe controllability problems, especially at the 4-knot speed. There are two factors to consider: available rudder and east wind.

At 4 knots, nearly hard-left rudder was initially required to hold the ship off of Stuart Island. Typically the rudder was put hard left and the maximum amount of RPM was used, short of exceeding the 4.5-knot maximum. At 6 knots, however, less than full rudder was required. The pilot could perform certain trade-offs: more rudder and less RPM. If he did not adjust ship RPM to varying conditions, ship speed might fall off slightly, but no appreciable loss in controllability would result. Finally when rounding Turn Point, the

ship was weathering a strong (40 knot) headwind, causing the speed to fall off. At 6 knots, the pilot could tolerate some decrease in speed, and did. At 4 knots however, with the ship just marginally under control, no speed loss could be tolerated, and greater attention was paid to ship RPM. There is, however, no easy explanation as to why the Puget Sound pilots should exhibit a greater standard deviation in speed.

3. CPA to Land Points

(See Figure 5-4). For the runs through Rosario Strait, there was a tendency for the Sandy Hook pilots to maintain greater CPAs to the selected land points ($p < .10$). This effect was most pronounced with respect to Village Point ($p < .15$) for the interactions of home port and location within Rosario. It was expected that CPA to various points of land would provide a reasonable performance measure for the effect of ship speed or controllability. Such a performance measure would eliminate the requirement for establishing an arbitrary track line to be adhered to by all test subjects. As it turned out, the CPA to specified land points did not reveal any significant difference in performance between 4 and 6 knots of ship speed. This may have been due to learning effects, the small sample size used together with large individual differences in pilot's performance or some other confounding effects. There was, however, a very definite opinion voiced by all test subjects that 4 knots was an unsafe speed at which to proceed. They all felt that the controllability of the ship was marginal at such a low speed. In addition, the one confirmed grounding that occurred in a track-keeping run took place with the ship running at 4 knots. The ship ran aground in the shallow waters off Village Point (Figure 5-5).

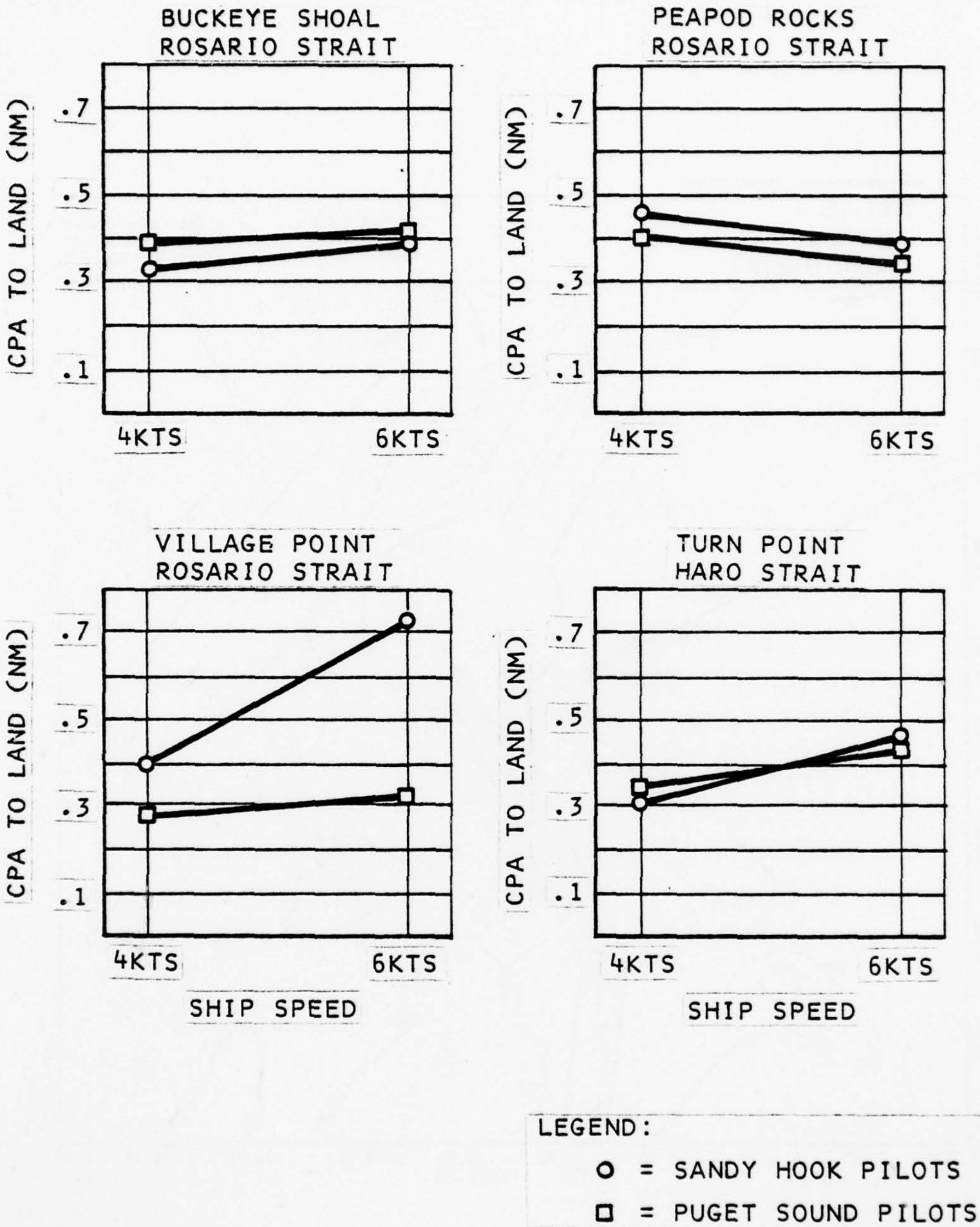

Figure 5-4. CPA To Land For Track-keeping Runs

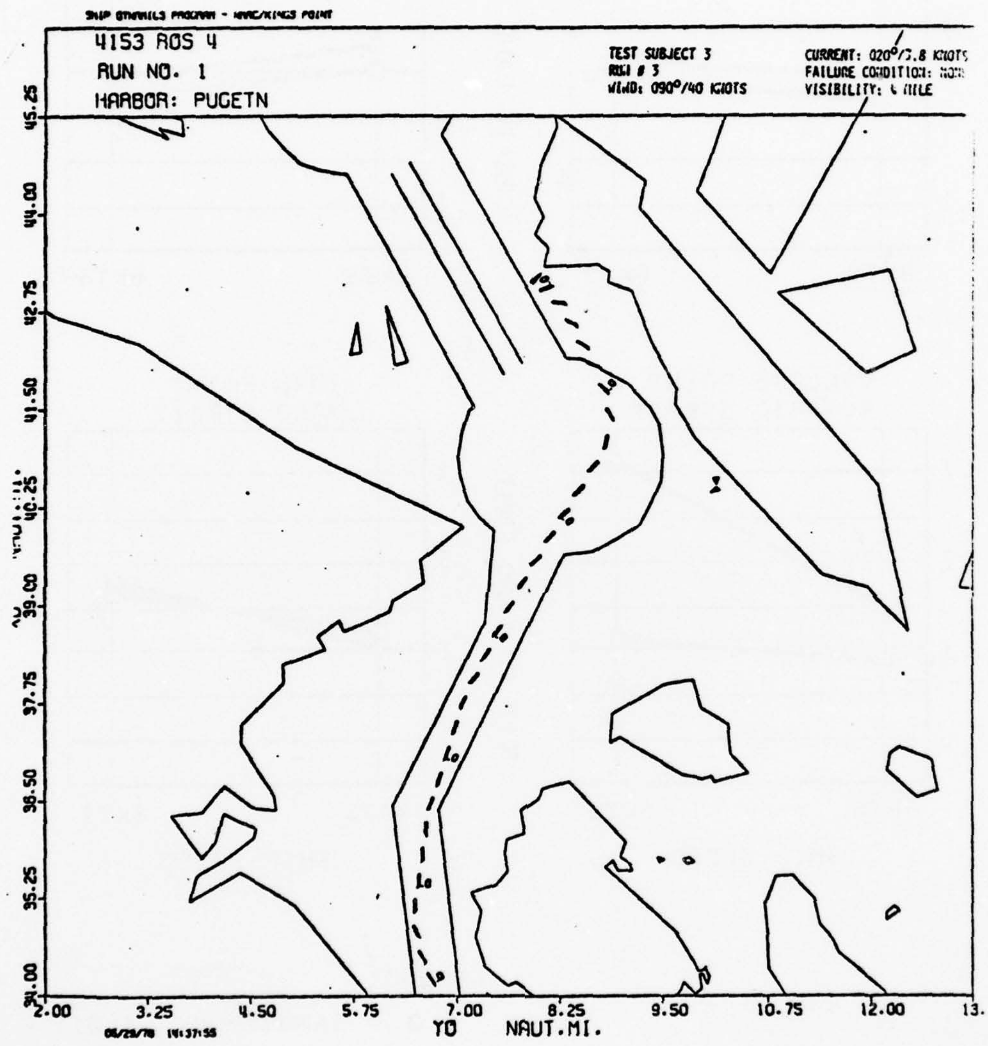

Figure 5-5. Man-In-The-Loop Run Resulting in a Grounding

The fact that the Sandy Hook pilots should have remained significantly further away from land is not surprising. They took more frequent bearings and, by using a preponderance of rudder rather than course commands, maintained a greater degree of control over the progress of the ship.

5.4.4.2 Effects of Ship Speed

1. Bridge Activity. Subjects tended to give more course commands at 6 knots then at 4 knots in the Rosario runs, whereas they gave fewer course commands at 6 knots than at 4 knots in the Haro runs (interaction of location and ship speed, $p < .025$). Sandy Hook pilots tended to take bearings more frequently at 6 knots than at 4 knots, whereas Puget Sound pilots took bearings more frequently at the lower ship speed (interaction of home port and ship speed, $p < .10$). In addition, subjects took bearings more frequently in Rosario than in Haro during the 4-knot runs but took bearings with equal frequency in the two locations at 6 knots (interaction of ship speed and location, $p < .10$). RPM commands were more frequent in the 4-knot than in the 6-knot runs ($p < .05$), an indication of the overall difficulty of ship controllability at such a low speed.
2. Ship Performance Measures
   An interaction of ship speed and location ($p < .01$) indicated subjects made the 6-knot runs through Rosario at significantly greater speed ($\bar{v} = 5.94$) than through Haro ($\bar{v} = 5.49$).
3. CPA to Land Point
   No effects due to ship speed approached statistical significance. There are, however, several comments which can be made on this subject.
   i) each test subject expressed the concern that maneuvering a 165,000 DWT tanker through Rosario Strait

under the prescribed conditions at 4 knots of ship speed was unsafe. They all felt that a higher speed was required to maintain controllability. There is no conclusive evidence on what higher speed is safe for these extreme conditions. It appears not to be 6 knots, but somewhat higher.

Figure 5-6 contains the plots of each subject's 4 and 6 knot track-keeping up Rosario Strait. An examination of the overshoot in the northern part of the run as the ship makes the course change to port indicates that:

- in two cases, the 6-knot run is somewhat better than the 4-knot run
- in one case, the 6-knot run is somewhat worse than the 4-knot run
- in one case, the 6-knot run is approximately equal to the 4-knot run

When order effects and sample size considerations are taken into account, it becomes clear that one may not reach any definitive conclusions about the differences in the safety of passage between the 4- and 6-knot conditions. Based upon subjective pilot reports, 6 knots is undoubtedly safer than 4 knots, but may still not be safe enough. The reader is reminded that all of these considerations must be viewed in light of the extreme environmental conditions used in this study. With lesser wind and current conditions, there may well have been a significant improvement at the 6-knot level.

ii) the above comments bear directly on the interpretation of the previously described off-line track-keeping runs. Figure 5-7 shows the 4-, 6-, and 8-knot runs made by the 165K tanker in Rosario Strait

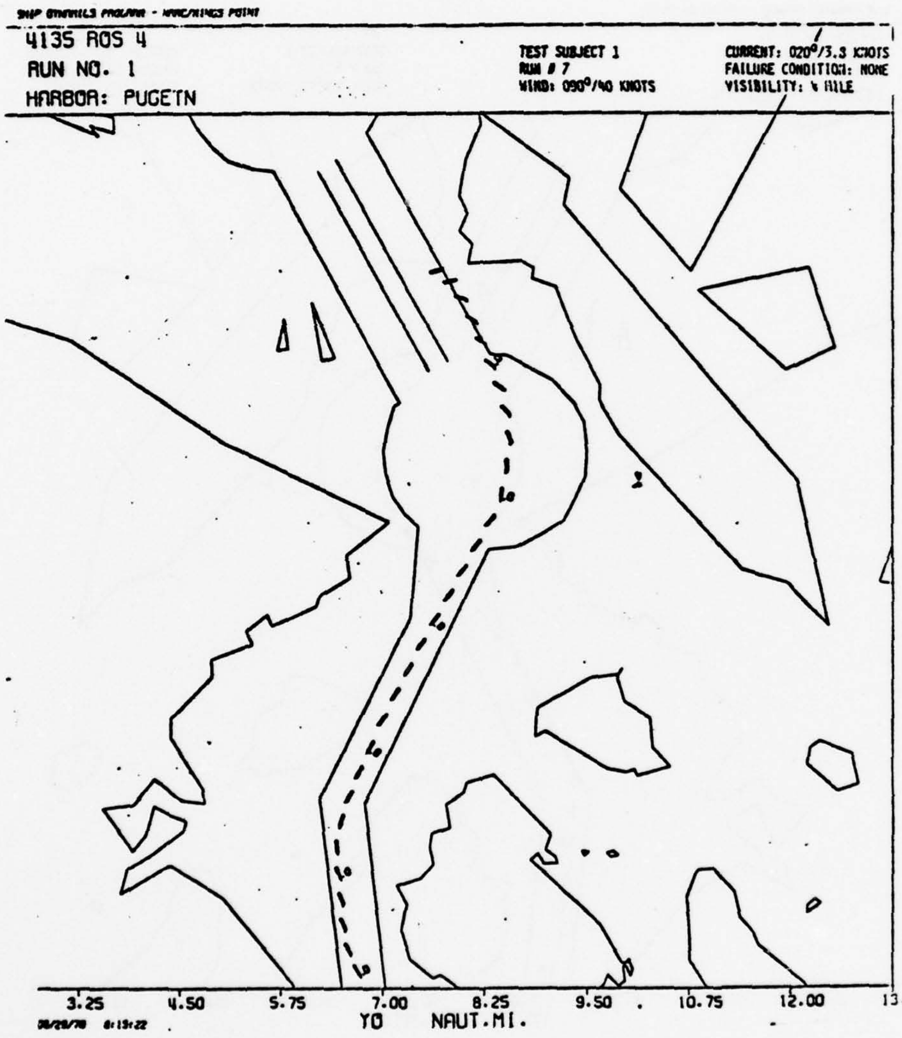

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 1, 4 Knots)

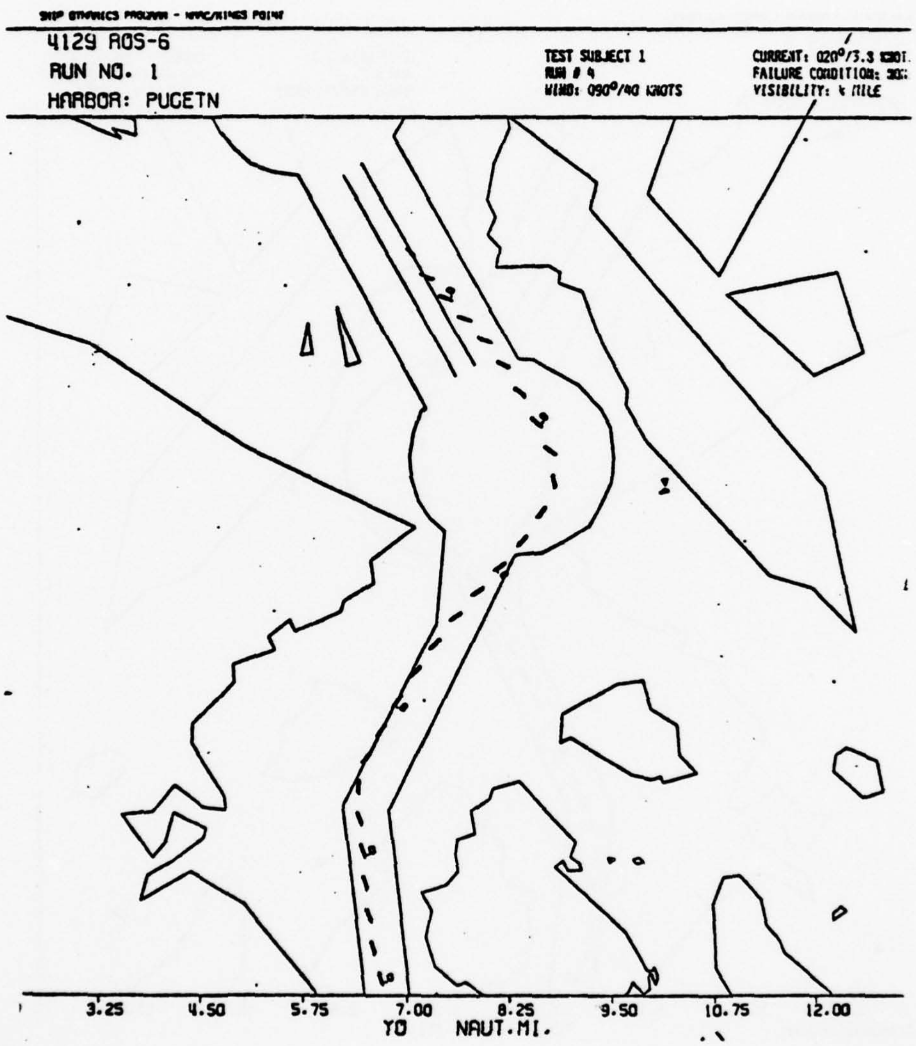

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 2, 6 Knots)

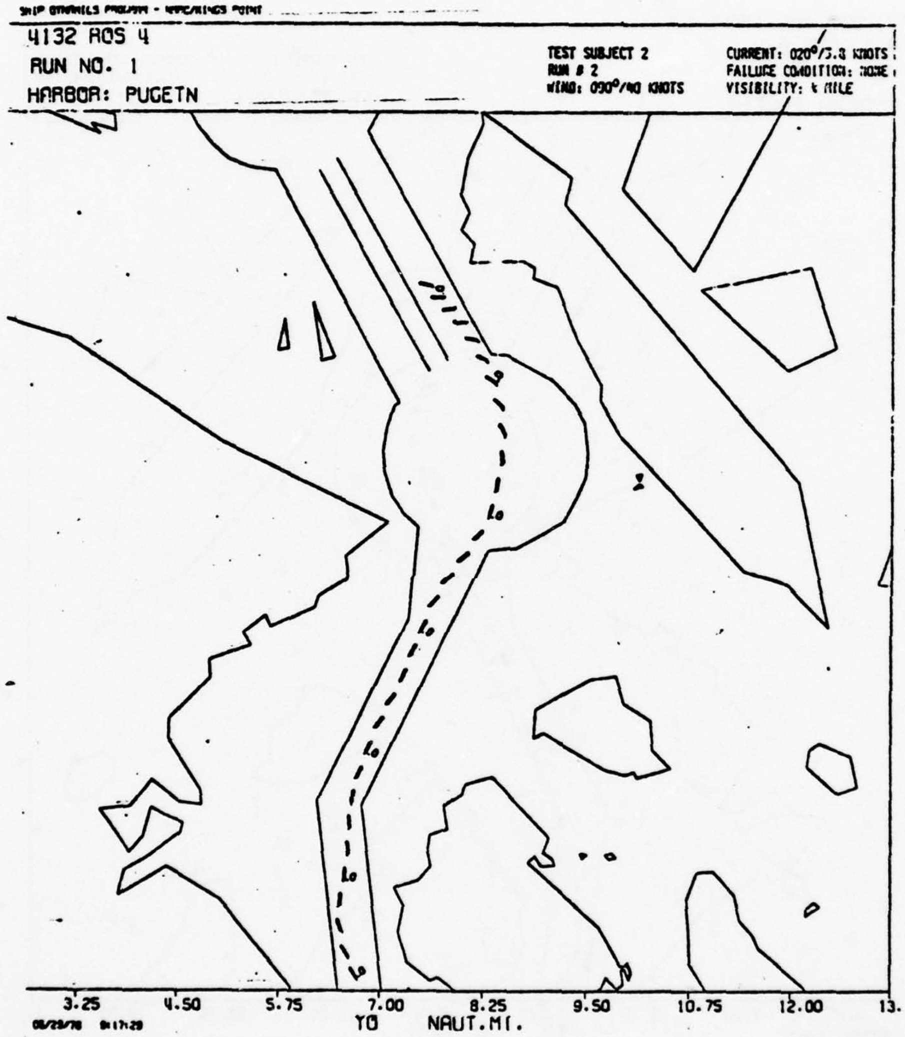

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 3, 4 Knots)

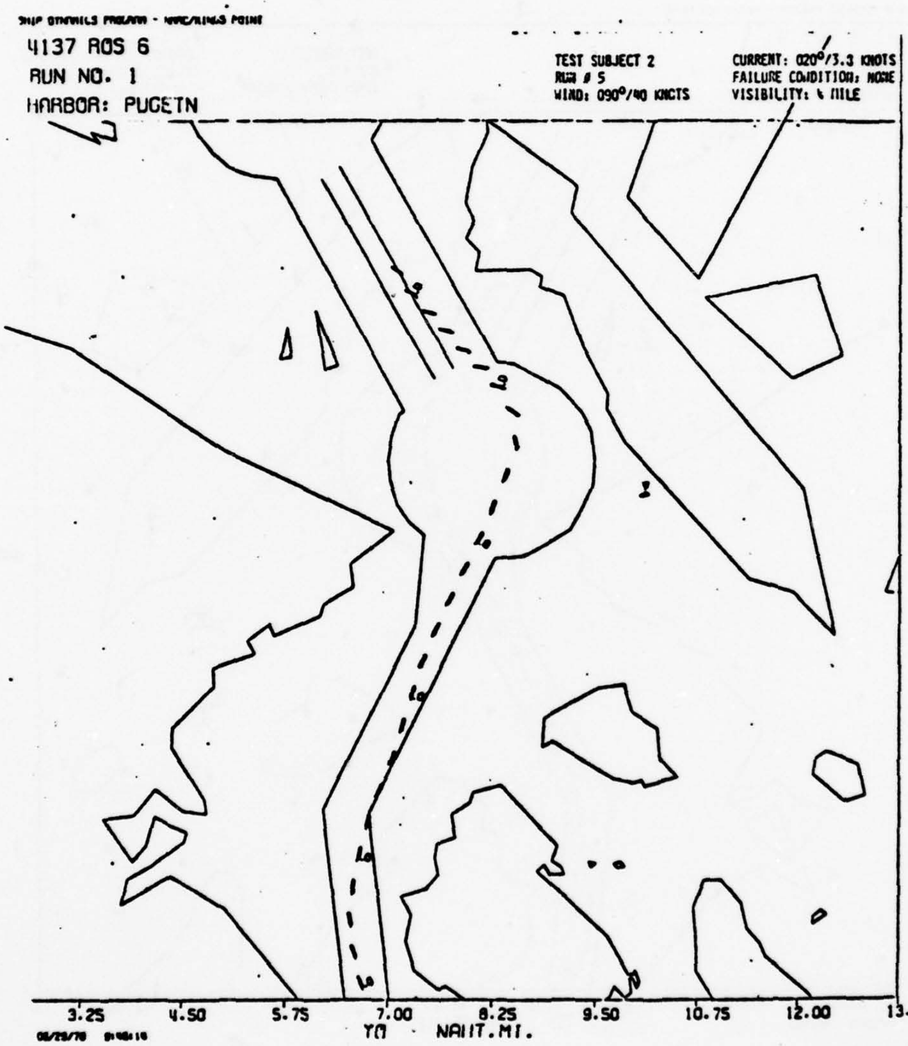

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 4, 6 Knots)

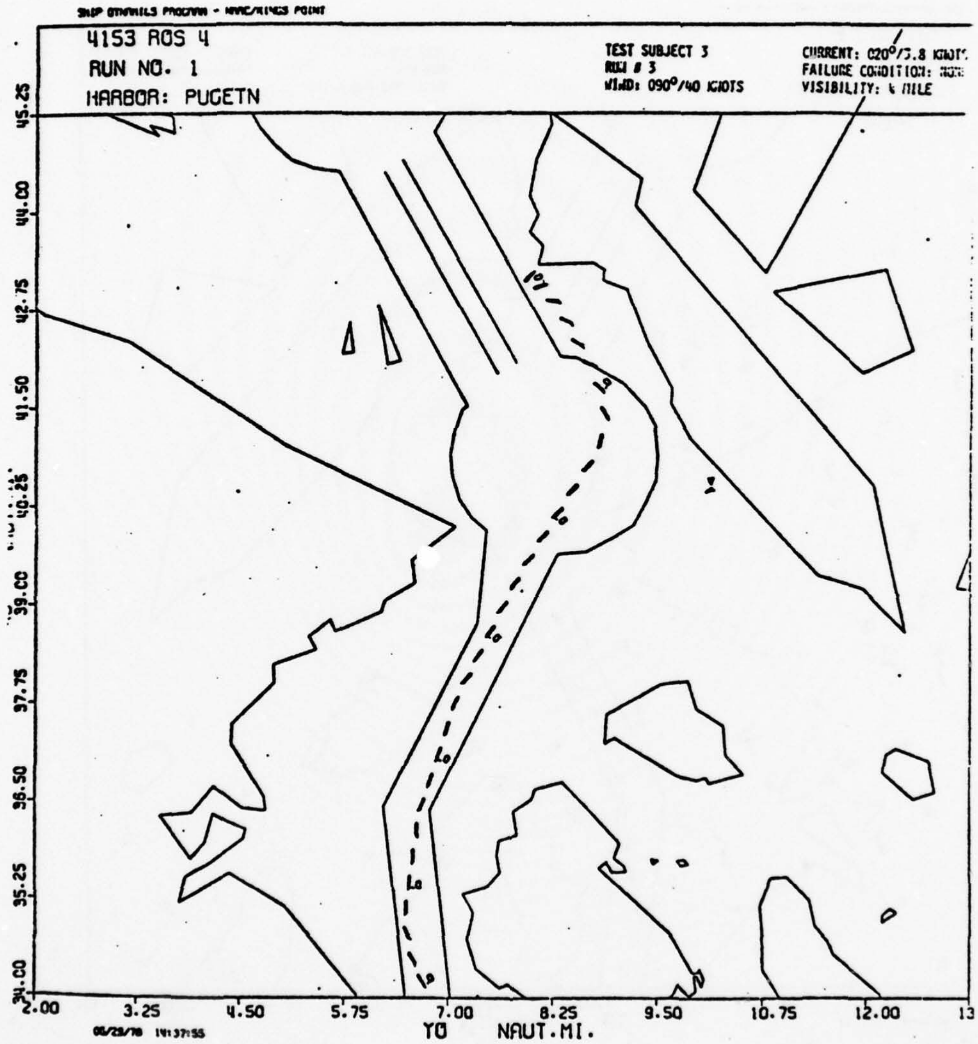

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 5, 4 Knots)

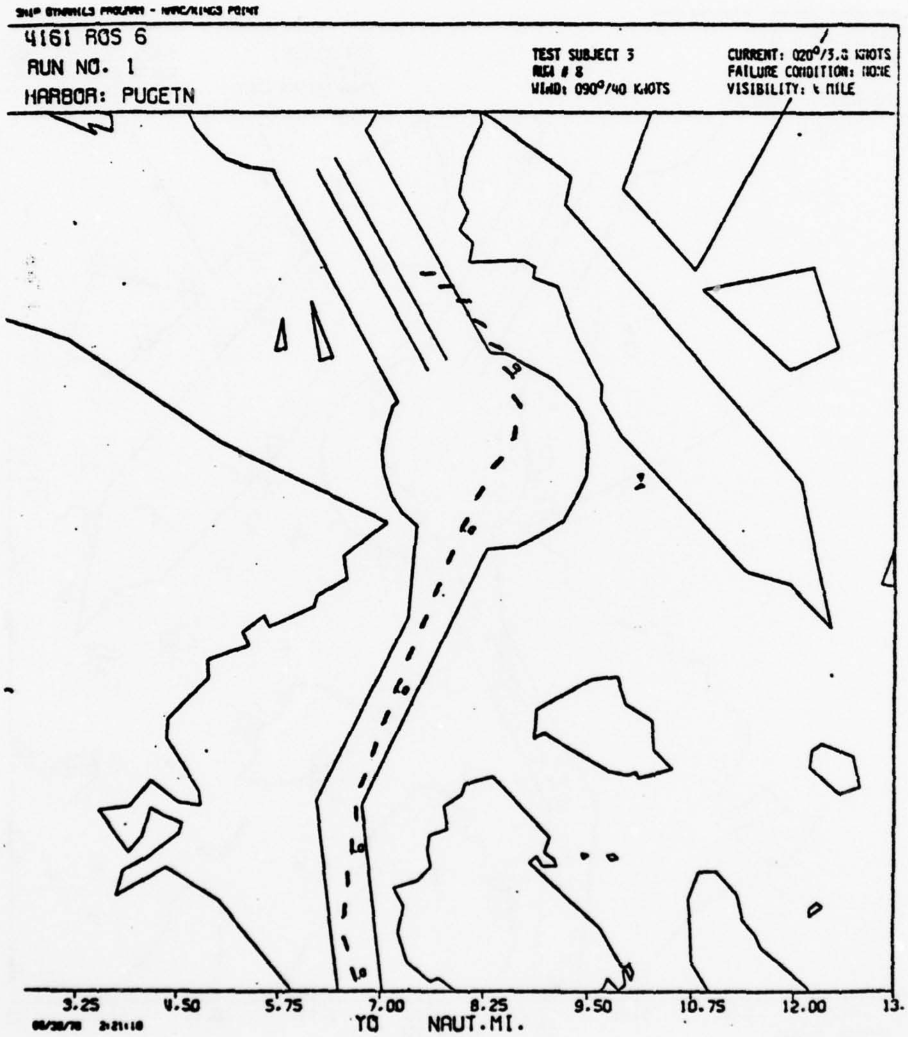

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 6, 6 Knots)

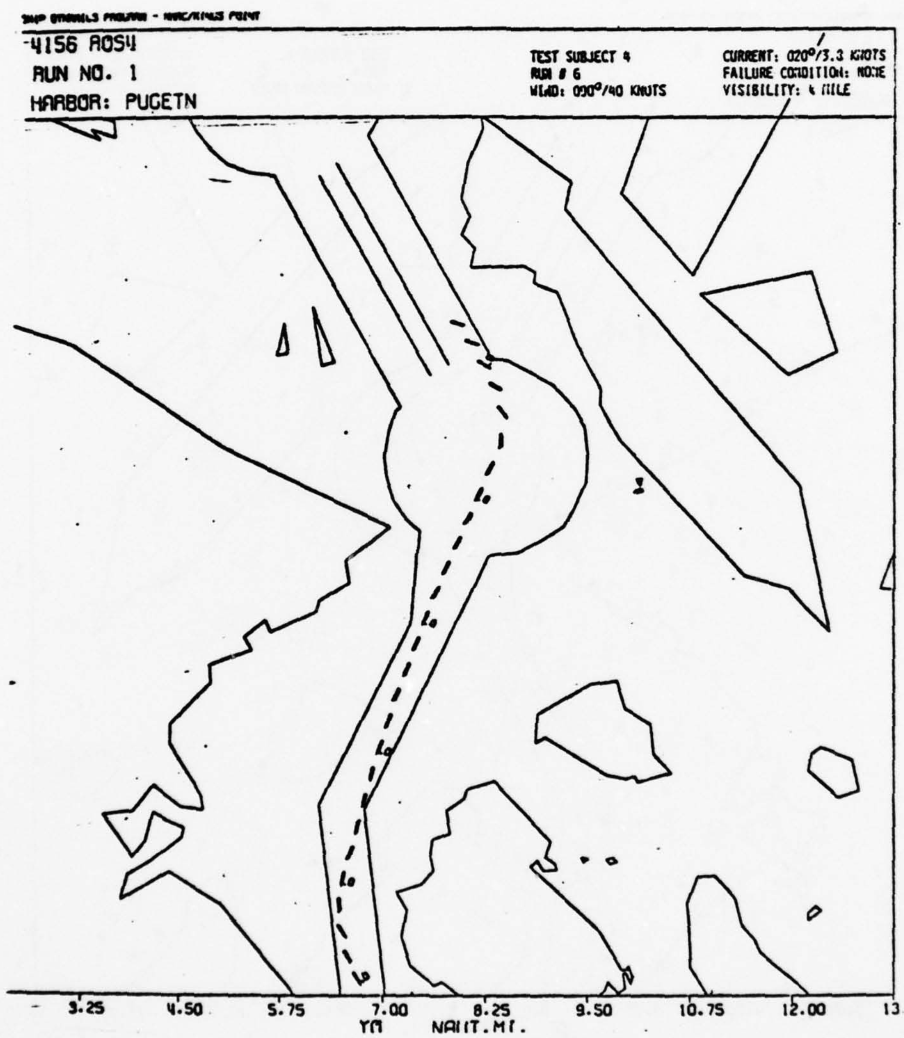

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 7, 4 Knots)

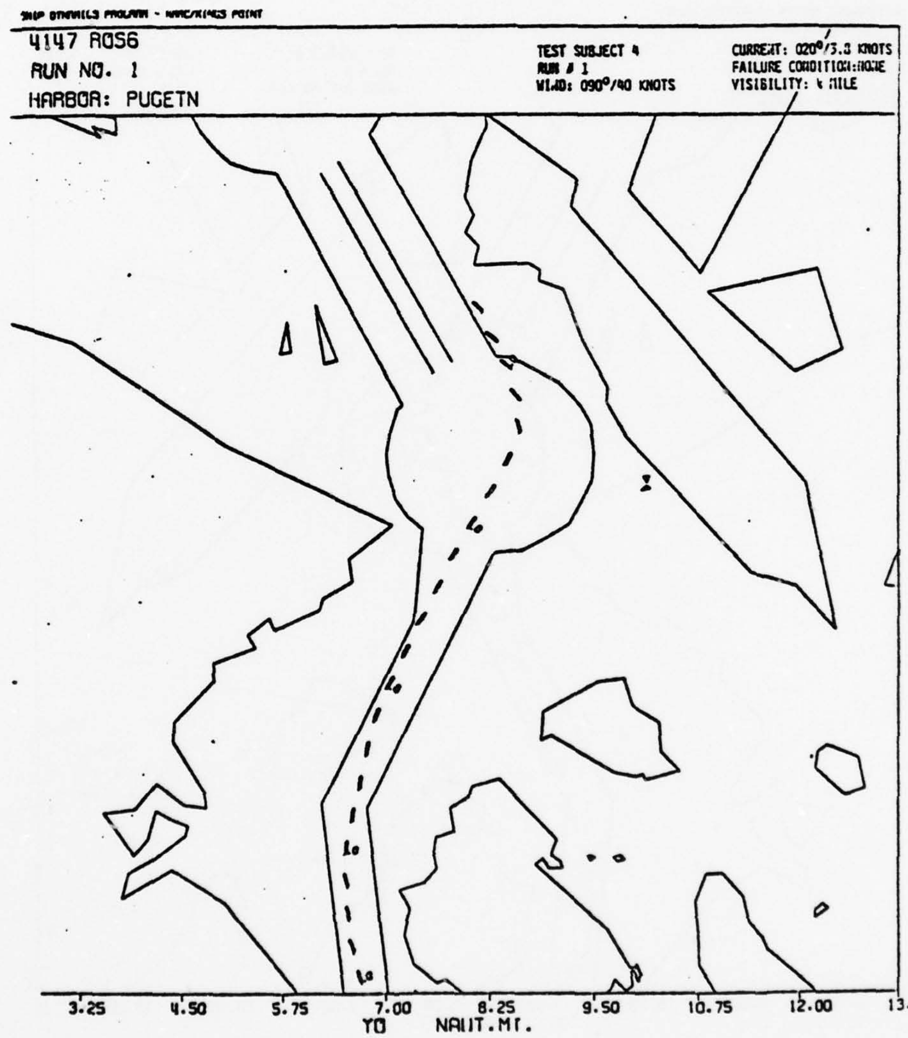

Figure 5-6. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 8, 6 Knots)

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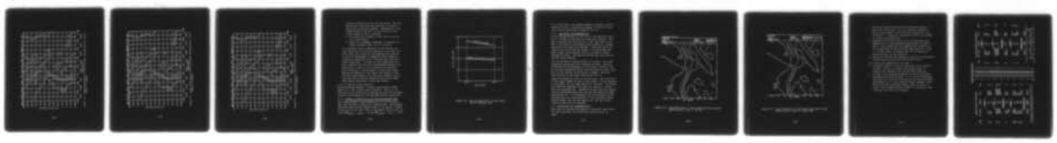

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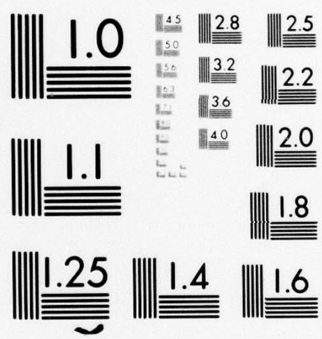

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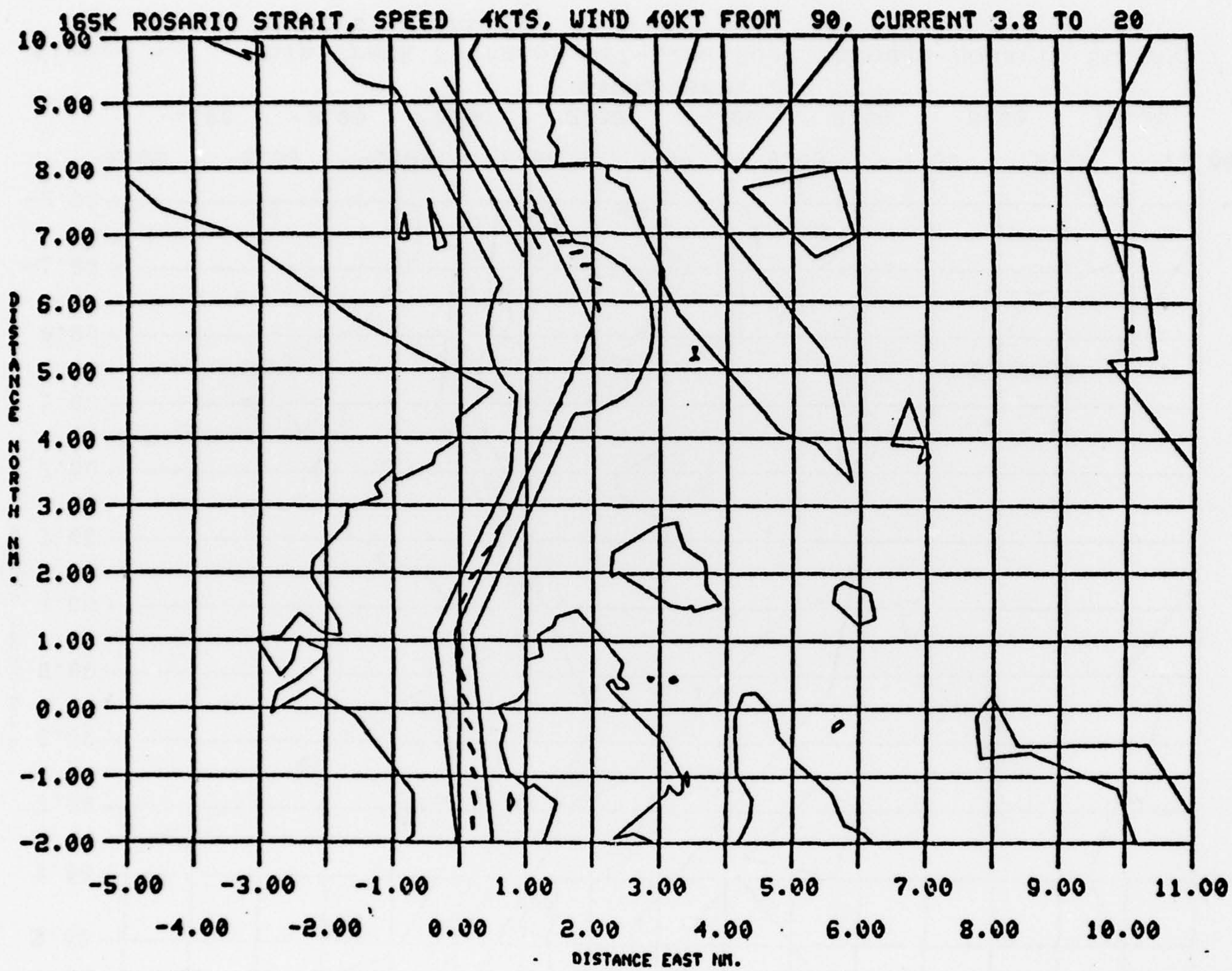


Figure 5-7. Ship Track Plots of Off-Line Runs Through Rosario Strait (Part 1, 4 Knots)

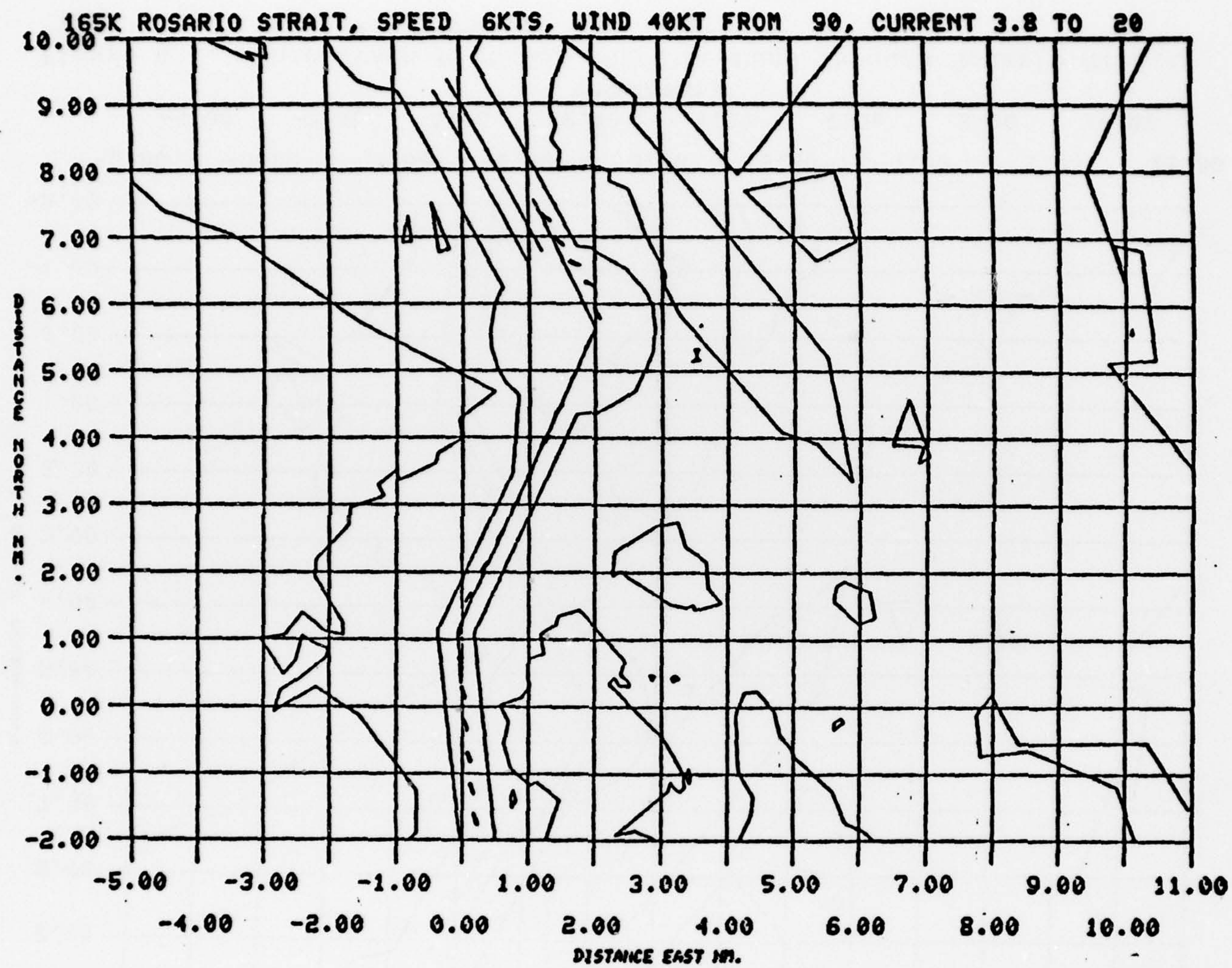


Figure 5-7. Ship Track Plots of Off-Line Runs Through Rosario Strait (Part 2, 6 Knots)

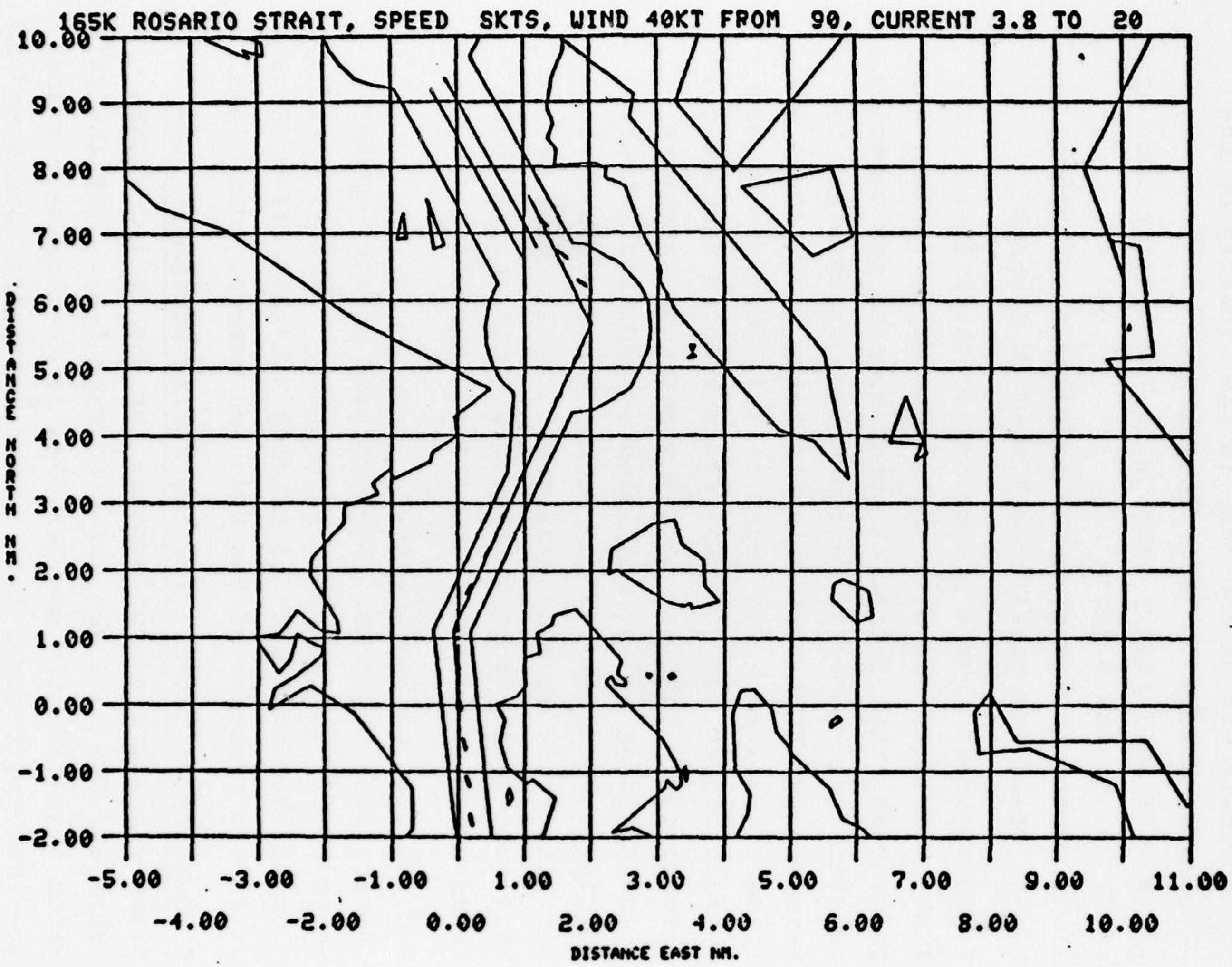


Figure 5-7. Ship Track Plots of Off-Line Runs Through Rosario Strait (Part 3, 8 Knots)

using an autopilot in the off-line study. The wind and current conditions are identical to those to which the pilots were exposed. Examination of the northern end of the run, in the vicinity of the course change to port, indicates

- the ship easily remains in the traffic lane at 4, 6, and 8 knots
- there is a systematic decrease in overshoot as speed increases from 4 to 6 to 8 knots

It is apparent from a comparison of the piloted (on-line) simulator run with the autopilot (off-line) computer runs, that autopilot track-keeping was superior to pilot track-keeping (a comparison which might be reversed by additional pilot training under these extreme conditions). In light of this comparison, one must interpret the off-line track-keeping results conservatively. That is, in the absence of extensive pilot training or the provision of additional track-keeping information to the human, the results of the off-line track-keeping runs are often somewhat better than that which could be expected from a pilot under these severe conditions of wind and current.

5.4.4.3 Effects of Run Location

Ship Performance Measures. Subject used greater rudder angles ($p < .05$) in Haro than in Rosario. This is a reflection of the difficulty of holding the ship off of Stuart Island in the presence of the wind and current conditions.

5.4.5 Summary of Results for the Failed Equipment Runs

The primary measure of performance for the failed equipment runs was CPA to Alden Point (Figure 5-8). The analysis indicated significantly smaller CPAs in the engine + rudder failure runs (with tugs) than in the engine failure runs (no tugs) ($\overline{CPA}_{engine + rudder} = .39$ nm; $\overline{CPA}_{engine} = .68$; $p < .025$).

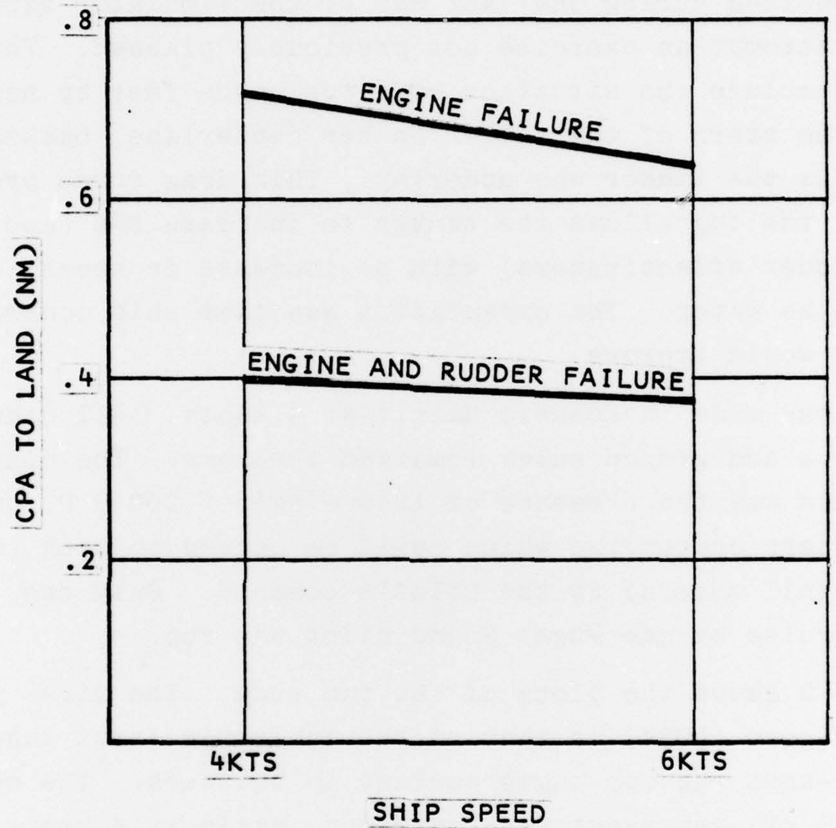


Figure 5-8. CPA To Alden Point In Haro Strait Failed Equipment Runs

It is clear that, even though severely limited by loss of propulsive power, a significant degree of control of the ship could be maintained throughout the run.

5.4.6 Additional Track-Keeping Run

It was decided during the last day of the simulator experiment to attempt an exercise not previously planned. That was to simulate the situation of a tug, made fast by her bow to the stern of the tanker on her centerline, backing down while the tanker was underway. This drag force provided by the tug allows the tanker to increase RPM (and hence rudder effectiveness) with no increase in speed through the water. The expectation was that ship controllability would improve.

The run was made in Rosario Strait at 4 knots. All other conditions and ground rules remained the same. The only difference was the presence of this single 7,200 H.P. tug on the stern centerline which could be caused to back (slow, half or full astern) at the pilot's command. Only one such exercise by one Puget Sound pilot was run.

Figure 5-9 shows the plots of the two runs. The first part of the figure (ROS4) is that of the subject's first exposure to the 4-knot run (no tugs) earlier in the week. The second part (ROS 4T) represents the same run, again at 4 knots, with the retarding tug. Inspection reveals that the subject actually performed worse with the tug (and additional RPM) than without it. It is possible that the presence of the tug made the pilot over-confident of the increased rudder effectiveness, the turn was begun late, and the current caused a great deal of overshoot.

5.5 CONCLUSIONS AND RECOMMENDATIONS

Recalling the extreme environmental conditions under which all runs were made, the following conclusions can be drawn:

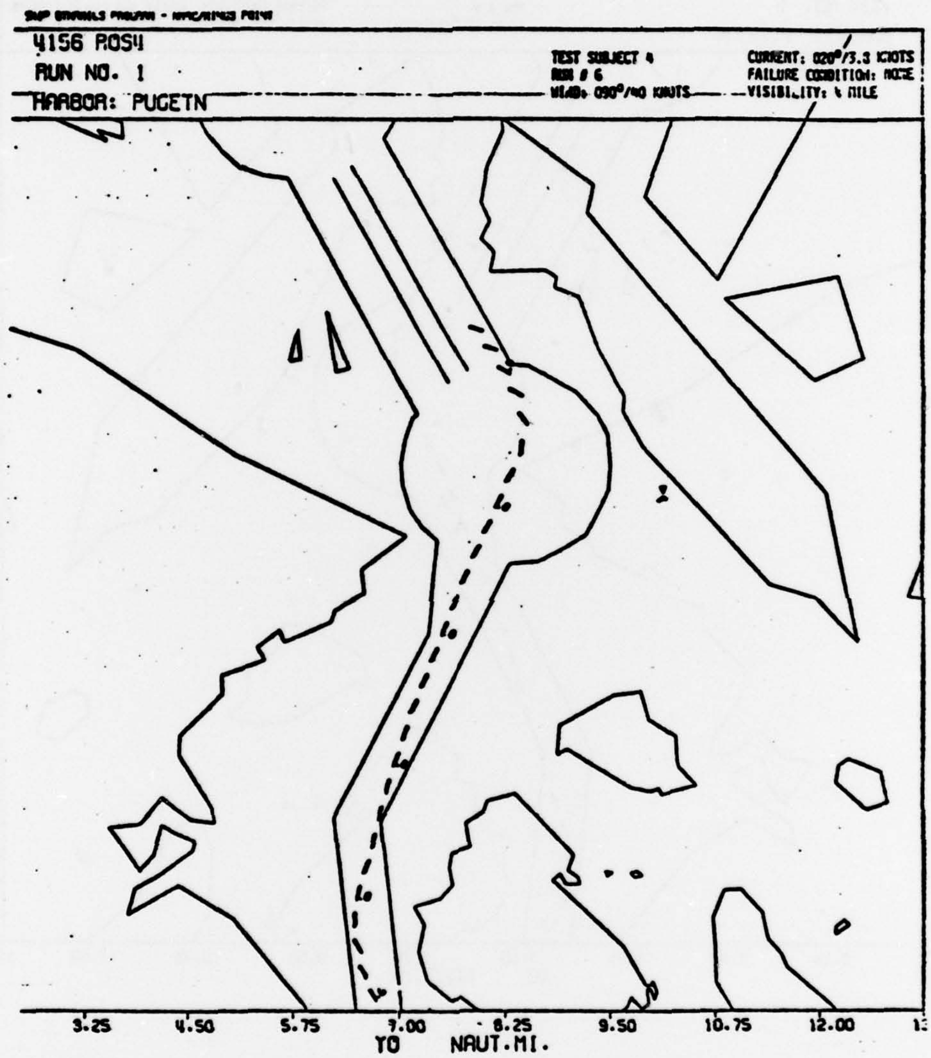


Figure 5-9. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 1, No Tug)

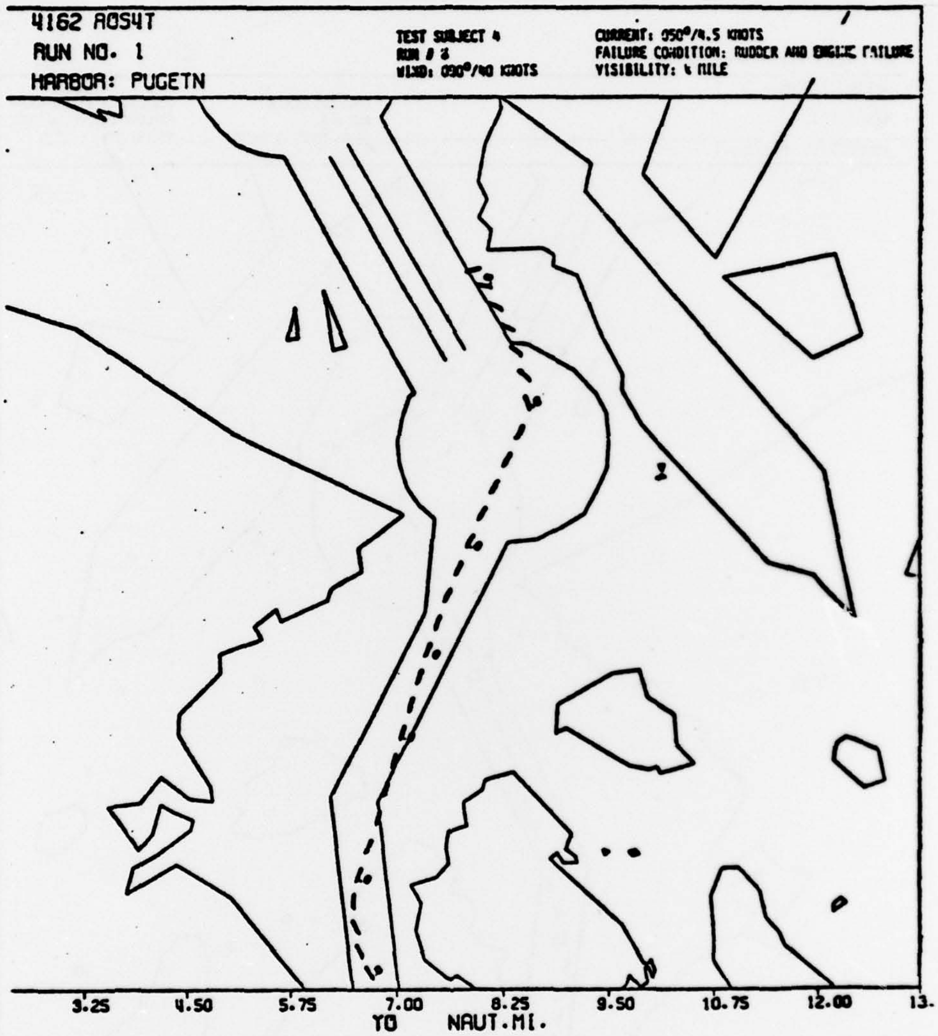


Figure 5-9. Ship Track Plots of Man-In-The-Loop Runs Through Rosario Strait (Part 2, Single Tug)

1. There were definite behavioral differences between 4 and 6 knot conditions. All test subjects regarded 4 knots of ship speed to be below the threshold for safe navigation. It does not necessarily follow that 6 knots is a safe navigating speed.
2. Comparison of on-line and off-line track-keeping data suggests that a safe navigating speed might lie near 8 knots. This comparison also suggests the advisability of interpreting the off-line data conservatively. That is, in many cases, the human could not be expected to perform as well as the autopilot.
3. There were definite and systematic behavioral differences between Puget Sound and New York Harbor pilots.

The following recommendations are made:

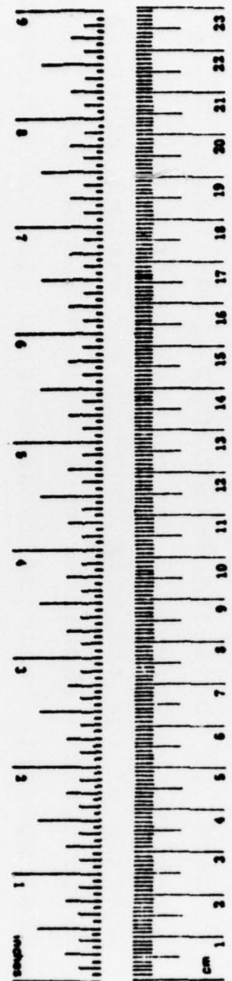
1. A greater number of runs with additional pilots should be made, in the 4- to 8-knot ship speed range, to identify the threshold for piloted controllability
2. A study of the training programs for various piloting organizations should be made. If it can be established that specific training is associated with more desirable performance (e.g., more frequent rudder commands, radar bearing and the consequent greater CPAs to points of land), then attempts should be made to incorporate such training into the pilot programs.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F